

A LIMIT CYCLING SPEED CONTROL SYSTEM

by

Hasan Kocaoglu



# United States Naval Postgraduate School



## THESIS

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CONTROL SYSTEM

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December 1970

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Hasan Kocaoglu  
Lieutenant (junior grade), Turkish Navy  
B.S., Naval Postgraduate School, 1970

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## ABSTRACT

The concept of a limit cycling control in power supplies and speed control has advanced the application of these broad areas. ON-OFF switching of a thyristor provides a simple and economical method of control and regulation. This switching of the thyristor causes the system to limit cycle.

Basic analysis and design of speed control was performed. A describing function was developed to model the power-supply and rectifier bridge. Then it was used to predict the frequency and amplitude of the limit-cycle.

A digital computer program was used to simulate the system response and to construct the describing function curves. To verify the describing function validity, the limit cycle predictions were compared with the simulated results.

Fourier analyses were performed to determine the ripple instability and subharmonic effect of the system output.





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## I. INTRODUCTION

Limit cycling control systems have enjoyed considerable popularity both in practice and in the literature. The practical reasons for which limit cycling systems have been developed are numerous, not the least important of which is the simplicity of an on-off power element. The first step toward such a theory was actually taken by Lozier (Ref. 6) at which time certain qualitative remarks were made. Thereafter it received little attention in the English literature. The paper by Li and Vander Velde (Ref. 7) represented an independent rediscovery of some fundamental principles regarding limit cycling control systems. Work of a similar nature has also recently been published in the U.S.S.R.

In this discussion stress is placed on considerations of the limit-cycling system as a control system and its signal transmission properties are derived as well as the loop limit cycle.

The discussion is limited to negative feedback configurations with a nonlinearity in the forward loop, such as shown in Figure 1.1. Here  $N$  stands for the nonlinearity, and  $G(s)$  for the loop linear elements. It is assumed that this is a limit-cycling system. That is, in the absence of an input, the system sustains a nearly sinusoidal undamped oscillation at its output. If, as is commonly the case, the function of this system is to reproduce the input signal at a higher power level at its output, then its response to a



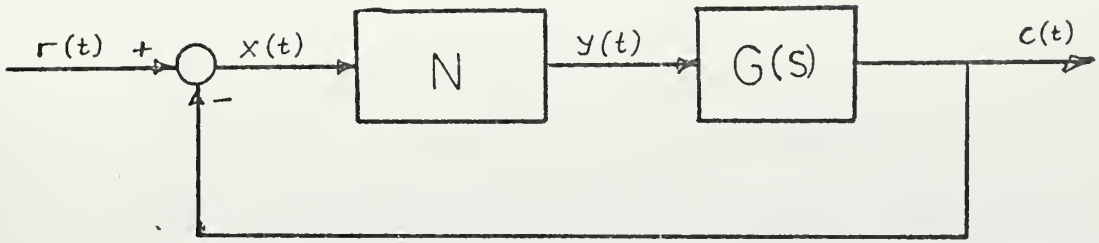


FIGURE 1.1: Simple limit cycling control system.

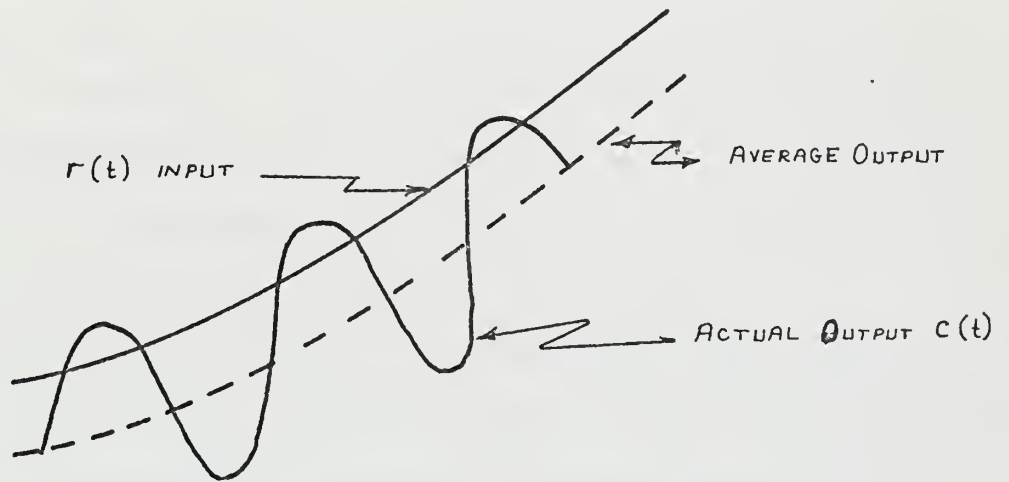


FIGURE 1.2: Typical input and its corresponding output.

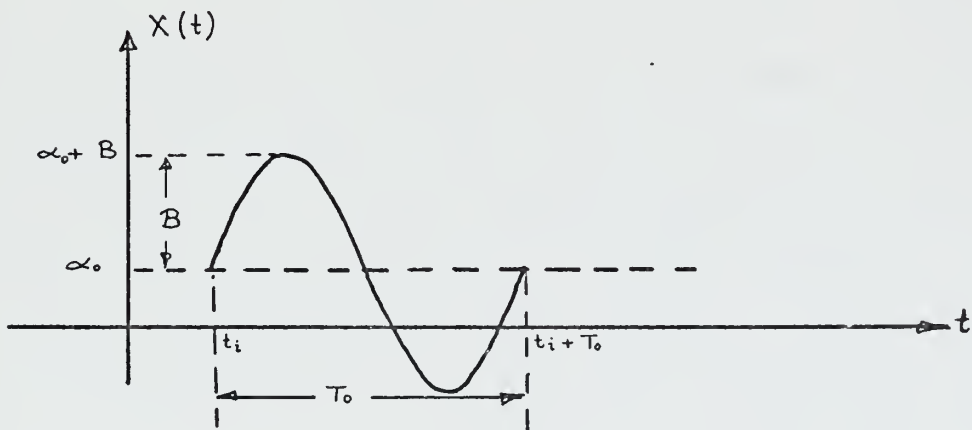


FIGURE 1.3: Model of  $x(t)$  over any limit cycle.



slow input signal might look as shown in Figure 1.2. For a well-designed control system the output follows the input on the average, within some dynamic following error. Over any period of the limit cycle,  $T_o$ , an approximate model of this error signal is shown in Figure 1.3. In this model the sinusoid of amplitude  $B$  is associated with the limit cycle, and the D-C bias of amplitude  $\alpha$  with the input forced following error.

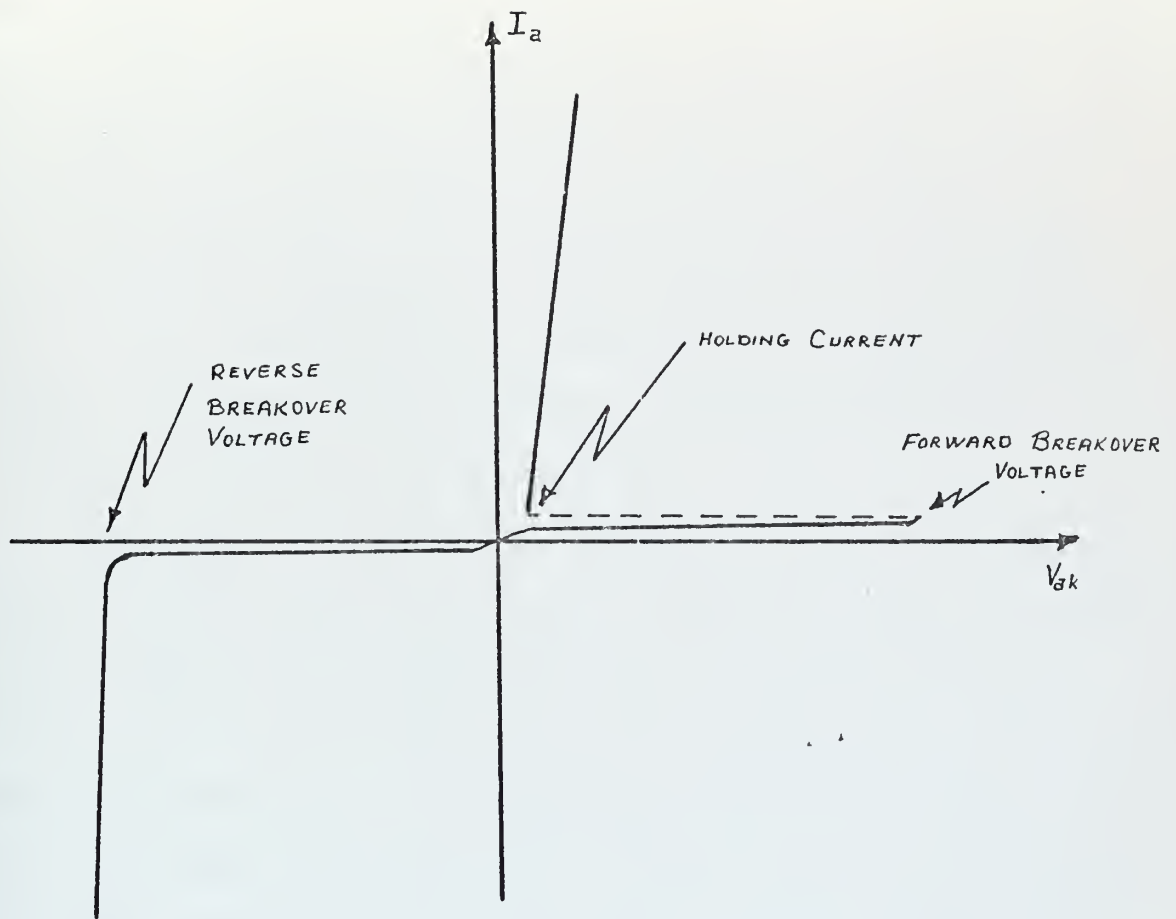
In this study a system which has properties mentioned above will be examined. The specific system to be examined is an armature voltage controlled D-C motor. Its armature is supplied with a poly-phase, thyristor, A-C to D-C rectifier and its field excited by a separate D-C source.

The goal in this study is to investigate the control of speed of this D-C motor, operating under forced limit cycling conditions. A mathematical model is proposed and then analyzed using frequency response techniques.

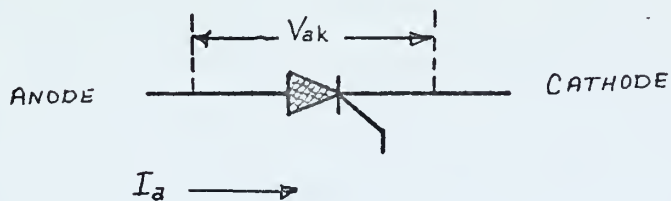
The thyristor, which is used in the rectifier bridge is a four layer, three terminal solid-state device. Functionally it is equivalent to its gas tube counterpart, a thyratron. The characteristics and circuit symbol of the thyristor are shown in Figure 1.4. In the forward direction the device has two stable modes of operation, one of high impedance, of similar amount to that in the reverse direction and the other, of very low impedance. In general the forward break-over voltage is inversely proportional to the gate current. This indicates that the device could be controlled by controlling







a - Transfer characteristic



b - Circuit symbol

FIGURE 1.4: Thyristor transfer characteristics.



the level of gate current. The control of the forward break-over voltage provides the interval of the forward conduction and thus the amount of power per cycle may be regulated. In this paper it is assumed that the entire rectifier bridge is controlled as a unit rather than by individual device for each thyristor. The gates of all thyristors in the poly-phase bridge are connected in parallel and a single firing signal is provided to all devices. A simplified circuit diagram is contained in Figure 1.5.

Conceptually the system operates as follows: assume that the output speed is below the reference speed. The rectifier bridge is then supplied with an ON signal, and the bridge output to the armature of the D-C motor is a three-phase, full-wave rectified voltage. The filter action of the motor alternates the harmonics of this voltage and provides a relatively smooth speed at the output. When the speed rises above the reference level the bridge is supplied with an OFF signal. There is a time delay before the bridge turns off, because the shut off conditions for all thyristors must be met. The time delay is approximately of the order of  $\frac{1}{4}$  cycle of the supply frequency. In the OFF state the input voltage to the armature of the D-C motor is zero with reverse current essentially blocked. The bridge will remain in the OFF state until the output speed falls below the reference, whereupon the cycle will repeat itself. This limit cycling of the system is the particular area to be considered here.



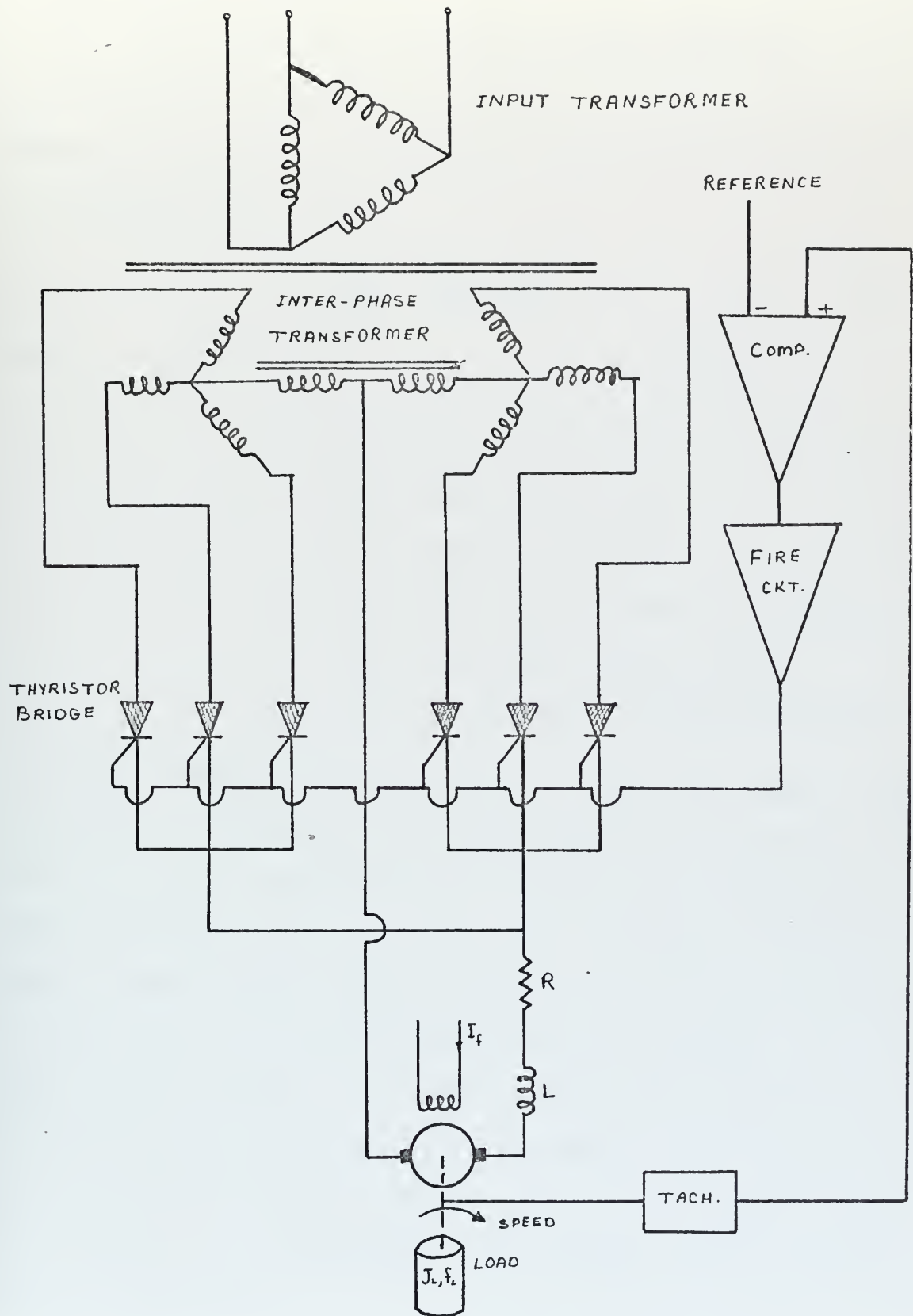


FIGURE 1.5: Simplified circuit diagram of the system.



## II. BASIC ANALYSIS AND DESIGN OF SPEED CONTROL

D-C motors with shunt excitation are particularly applicable for speed control systems. The speed of this motor can be expressed by

$$\omega_m = \frac{V_a - i_a R}{C_1 \phi} \quad (2-1)$$

where,

$\omega_m$  = Speed of motor

$V_a$  = Armature voltage

$i_a$  = Armature current

$R$  = Resistance of armature circuit

$\phi$  = Operating magnetic flux

$C_1$  = Coefficient of proportionality

It is apparent from equation 2-1, that the speed of such motors can be controlled either by varying the armature voltage,  $V_a$ , or the operating flux,  $\phi$ , that is, by varying the field-excitation current of the motor. However, the advantage of speed control characteristics of a D-C motor cannot be fully utilized unless an adjustable D-C voltage can be applied to the armature. In order to take full advantage of a D-C motor characteristics, it is necessary to provide an adjustable output voltage converter which would convert the A-C line voltage into an adjustable D-C voltage, which can be applied to the motor.





The very popular rotating converter consisting of an A-C motor driving a D-C generator, and known as the "WARD LEONARD" system, is one of the most widely used adjustable voltage supplies.

The rectifier converter, combined with complete electronic control and regulating system is perhaps the most practical unit available. Its prime advantage over the rotating type converters is that only one rotating machine is used instead of three. In addition, the compactness of the electronic system, the flexibility for adaptation to various conditions, accuracy, and sensitivity are improved.

The particular interest here is to control the speed of a D-C motor by controlling the conduction angle of the thyristors, which are used as an A-C to D-C converter to supply the armature of the motor as shown in Figure 1.5. In this configuration a feedback control system was employed to achieve the desired performance.

The system in its simplest block-diagram form is illustrated in Figure 2.1. In order to permit analysis, the system components are lumped and partitioned as illustrated in Figure 2.2. In this figure, block " $G_2$ " represents the motor and load. It is assumed that they are entirely linear. Block " $G_1$ " is included to take into account any gain that may be associated with the comparator, firing circuit, and compensation network which may be added to the system. Again, this block is assumed to be linear. The source and rectifier bridge are represented as block "N" which is assumed to have a periodic input and output for development of basic describing



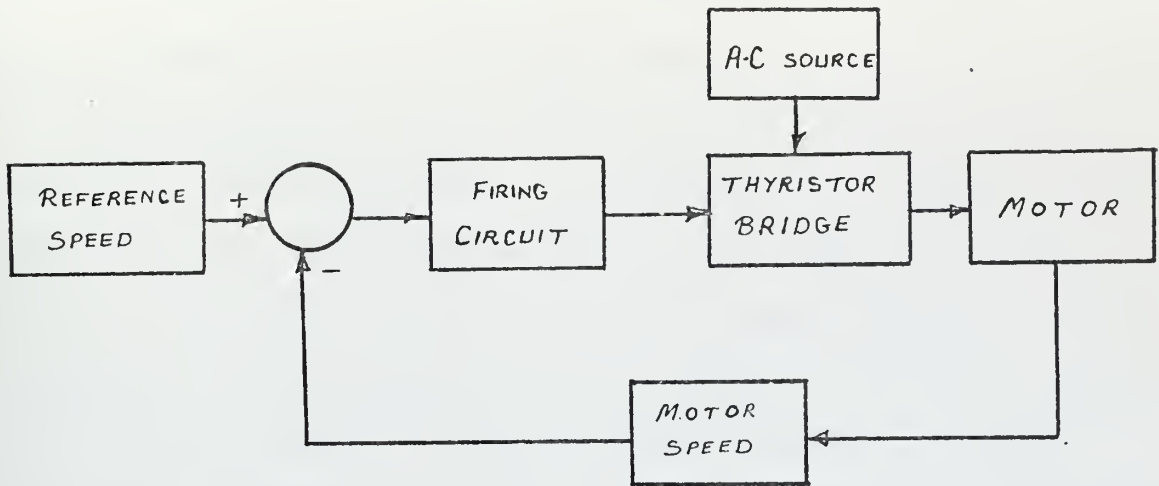


FIGURE 2.1: Block diagram for regulated speed control.

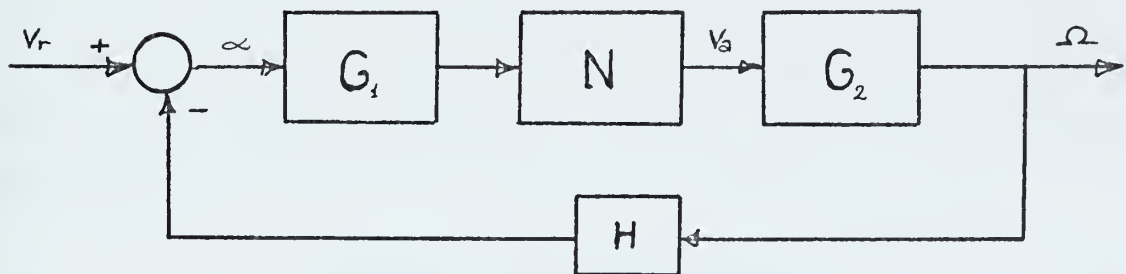


FIGURE 2.2: Simplified block diagram.



function (which will be mentioned later in this study). The general nature of this block is nonlinear. Block "H" represents a conversion factor of the speed to the voltage. It can be considered as a feedback gain.

The principle of operation can be described as follows: the speed setting voltage,  $V_r$ , represents the desired motor speed, and the tachometer gives  $K_t$  per radian per second, which is directly proportional to the tacho generator speed. Regulation of tachometer voltage is equivalent to the regulation of motor speed. The difference between  $V_r$  and the tachometer voltage,  $K_t\omega_m$ , is an error signal which can be represented as

$$\alpha = V_r - K_t\omega_m \quad (2-2)$$

This signal shows the deviation of the motor speed from its desired value. The purpose of the automatic speed control is to minimize this error signal and obtain the desired value of the speed. This error signal operates the firing circuit, it controls the motor speed by adjusting the conduction angle of the thyristors in the rectifier bridge, thus altering the average current and voltage value of the armature circuit.

One procedure for analysis of the system is by using the conventional transfer function concept. The system transfer function is

$$\frac{\Omega(s)}{V_r(s)} = \frac{G_1(s)G_2(s)N}{1+G_1(s)G_2(s)H(s)N} \quad (2-3)$$

The linear portion of the system may be block diagrammed as shown in Figure 2.3.



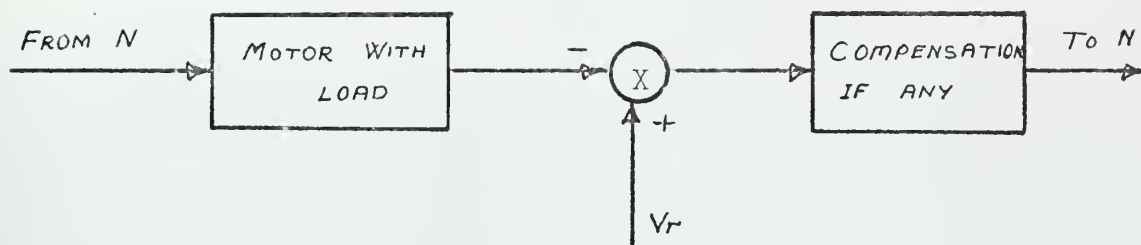


FIGURE 2.3: Block diagram for linear system.

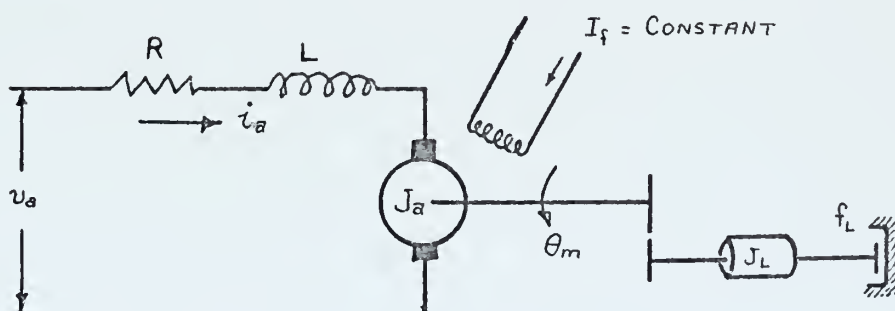


FIGURE 2.4: Motor and load.





The transfer function for the motor and load illustrated in Figure 2.6 is developed as follows. The loop equation for the armature circuit is:

$$V_a = i_a R + L \frac{d i_a}{dt} + K_m \omega_m \quad (2-4)$$

Torque-equilibrium equations are

$$T_d = K_t i_a \quad (2-5)$$

$$T_l = J \dot{\omega}_m + f \omega_m \quad (2-6)$$

From equations 2-5 and 2-6

$$\dot{\omega}_m = -\frac{f}{J} \omega_m + \frac{K_t}{J} i_a \quad (2-7)$$

and from equation 2-4

$$\dot{i}_a = -\frac{R}{L} i_a - \frac{K_m}{L} \omega_m + \frac{1}{L} V_a \quad (2-8)$$

are obtained.

Choosing state variables as:

$$X_1 = \omega$$

$$X_2 = i_a$$

$$\dot{X}_1 = -\frac{f}{J} X_1 + \frac{K_t}{J} X_2$$

$$\dot{X}_2 = -\frac{K_m}{L} X_1 + \frac{R}{L} X_2 + \frac{1}{L} V_a$$

A signal flow graph of the system is given in Figure 2.5, with 1/s indicating an integration and  $X_{10}$  and  $X_{20}$  as initial conditions.



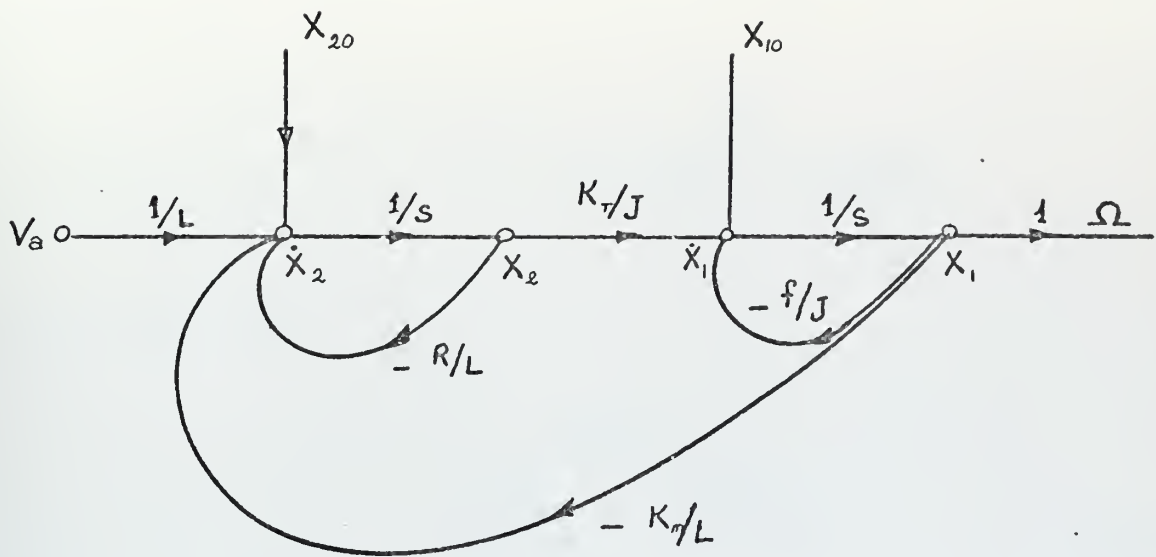


FIGURE 2.5: Signal flow graph for linear system.



Using Mason's gain rule the transfer function in Laplace notation is:

$$G_2(s) = \frac{\Omega}{V_a} = \frac{\frac{K_t}{JL}}{s^2 + \frac{RJ+Lf}{JL}s + \frac{Rf+K_tK_m}{JL}} \quad (2-9)$$

or in Bode form

$$G(s) = \frac{\frac{K_t}{Rf+K_tK_m}}{\frac{JL}{Rf+K_tK_m}s^2 + \frac{RJ+Lf}{Rf+K_tK_m}s + 1} \quad (2-10)$$

Numerical values for the motor parameters and load were selected from Reference 1, Chapter 7, Problem 9.

They are:

Armature resistance	$R = 0.08 \text{ ohm}$
Armature inductance	$L = 0.008 \text{ Henry}$
Motor torque constant	$K_t = 0.95 \text{ Newton-meter/Amp}$
Motor e.m.f. constant	$K_m = 0.95 \text{ Volt-sec/Rad}$
Equivalent inertia of motor-load	$J = 1.38 \text{ Kg-m}^2$
Equivalent viscous friction of motor-load	$f = 0.086 \frac{\text{newton-meter}}{\text{rad/sec}}$
Feedback gain	$K_t = 0.318 \text{ Volt-sec/rad.}$

By using these values and computer program "LISA 360 A PROGRAM FOR LINEAR SYSTEM ANALYSIS 360 D-16 . 4 . 009", the values of magnitude in "db" and phase of the transfer function were calculated. From these data Bode plot and Nichols plot were obtained for limit cycle investigation. Plots were shown in Figures 2.6 and 2.7.



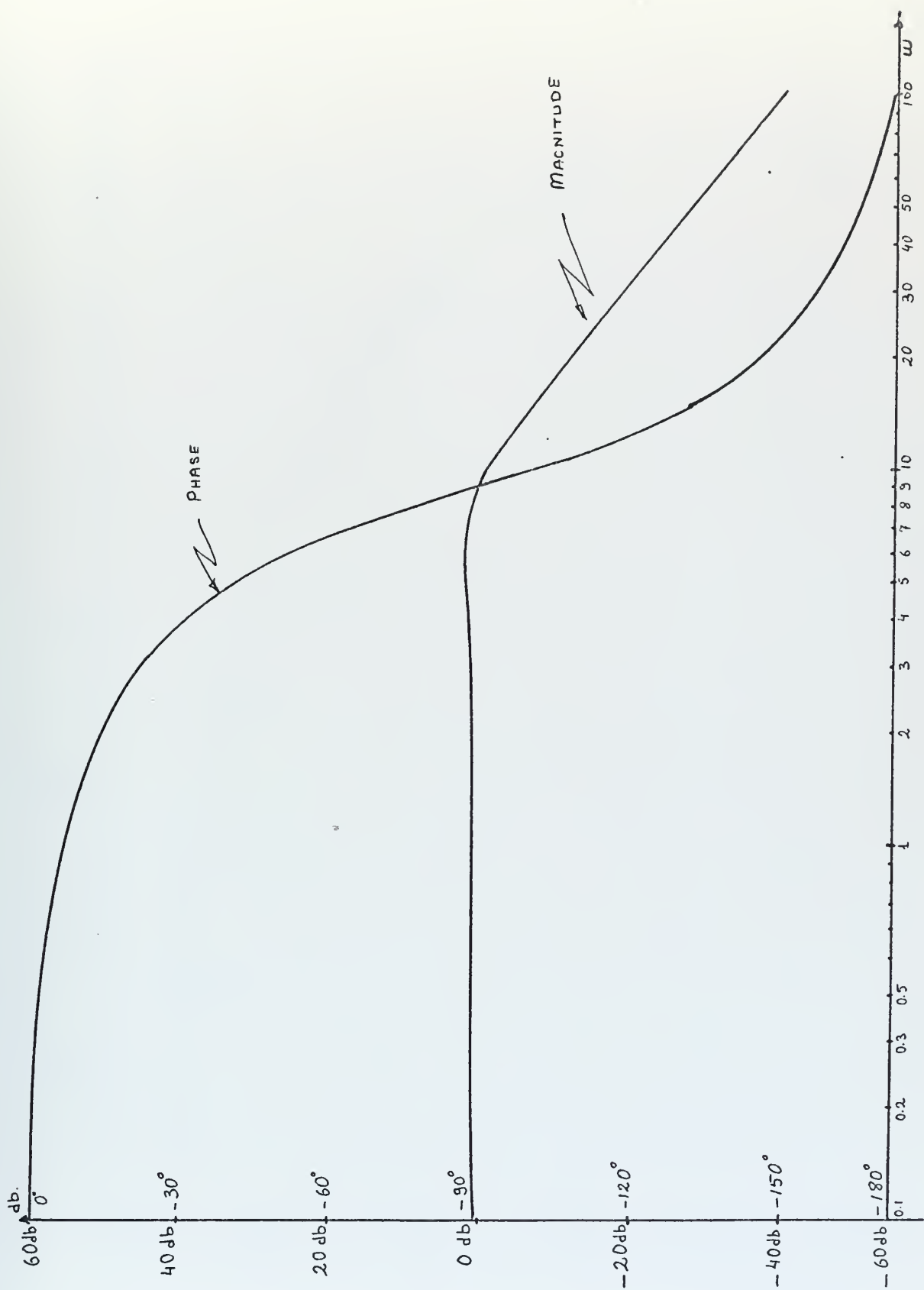


FIGURE 2.6: Bode plot for linear part.





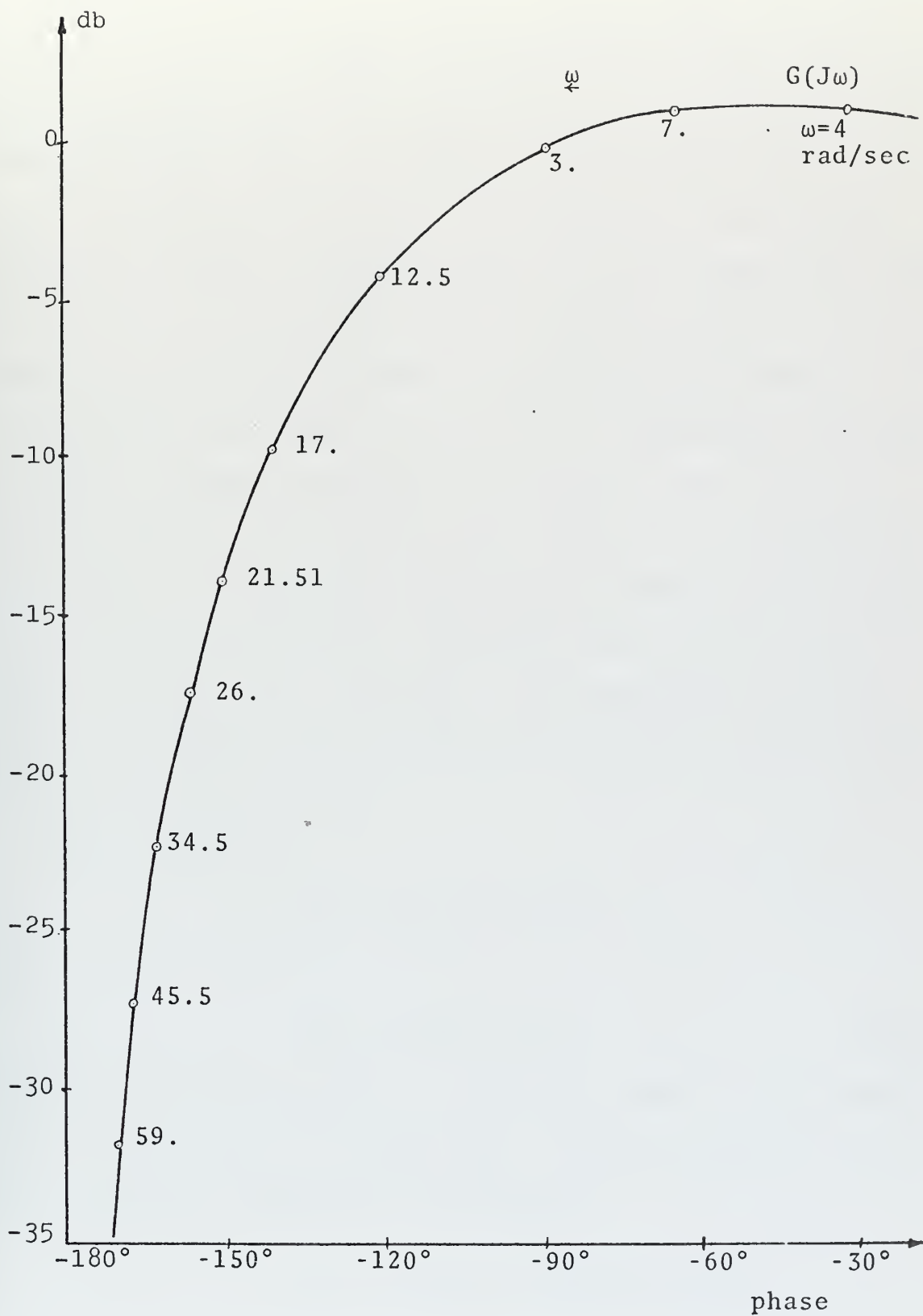


FIGURE 2.7: Nichols chart for linear part.



For a desired value of speed at a specified load, normal practice is to compute the value of firing angle that will produce the desired output, then design the firing circuit to produce a firing angle,  $\alpha_0$ , that biases the rectifier to the desired output. Thus, the basic design provides the desired result in open loop operation. The feedback loop is then designed to adjust the system when operating conditions change. If the load is changed this causes a change in speed which causes an error, and the error is amplified and changes the firing angle by an amount  $\beta$  in order to counteract the change in speed. In such a design it is necessary that the firing circuit gain,  $K_e$ , be chosen to give the desired steady state speed regulation, then the loop must be checked for stability and for transient response, since the gain is set on the basis of steady state accuracy. It is possible to use an open loop approach which includes the nonlinear characteristic of the rectifier.

From Figure 2.2,

$$\Omega(s) = G_1(s) N G_2(s)$$

and

$$\Omega(s) = G_2(s) V_a(s) \quad (2-11)$$

Assuming armature voltage is a constant, that is the average value of the rectifier output,  $V_{av}$ . Using equation 2-3 and motor parameters equation 2-11 becomes

$$\Omega(s) = \frac{86 V_{av}}{s(s^2 + 10.06s + 82.37)}$$



By applying the final value theorem which is

$$\lim_{t \rightarrow \infty} \omega(t) = \lim_{s \rightarrow 0} s \Omega(s)$$

The steady state value of speed was obtained as below:

$$\omega_{ss} = 1.045 V_{av}$$

It is known that the average value of the rectifier output is a function of the error signal,  $\alpha$ , and the sensitivity of the firing circuit to the error. If the sensitivity of the firing circuit is improved by using an amplifier and compensation network, better results can be obtained.

As mentioned before, operation of the system depends on existence of a difference between reference speed and measured speed. If the "control gain" of the system is defined as the tachometer output per volt applied to the amplifier when the feedback path is broken.

Control gain

$$G = \frac{K_t \omega_m}{\alpha}$$

Now when the loop is closed

$$\alpha = V_r - K_t \omega_m$$

Then,

$$G = \frac{K_t \omega_m}{V_r - K_t \omega_m}$$

$$K_t \omega_m = V_r \frac{G}{1 + G}$$

Thus, the greater the control gain, the closer will be  $K_t \omega_m$  to  $V_r$ . For high accuracy, high gain is required.



### III. PREDICTION OF LIMIT CYCLE CHARACTERISTIC

Procedures for analysis of the linear portion of the system have been previously established by using the transfer function concept. It is desirable to extend these techniques to the analysis of the nonlinear part of the system. Actually, for the nonlinear portion there is generally no exact method for relating the output to the input, in closed form. Most techniques of nonlinear analysis use some sort of approximation, that is, assumed linearity of the system over the desired range of operation to be considered.

The extension of the transfer function representation is more difficult. It requires that the nonlinearity be described by an equation in the frequency domain, and it also requires that, this equation be compatible for use with the transfer functions of the linear components. Practical solution to these requirements is the describing function technique which makes the approximation in the frequency domain.

The basic philosophy of the describing function is that the open-loop control system is excited at its input by a sinusoidal forcing function. The output of the nonlinearity is periodic and can be represented by its Fourier series. This is illustrated in Figure 3.1.

Certain assumptions must be made in the process of this linearization, that the input to the nonlinear component is a pure sine wave, and linear portion of the system following the nonlinearity is a low-pass filter, which is commonly true





in most physical feedback control systems. Thus it is assumed that the only terms of the Fourier series that are passed to the output of the system are the D-C term and the fundamental frequency term. The fundamental frequency term in the Fourier series has the same frequency as the input signal but may differ in amplitude and phase. When the loop is closed this harmonic will propagate itself around the loop and result in a continuous oscillation of the system. Then the describing function may be defined as the ratio of the fundamental term in the Fourier series for the output wave to the input sinusoid considering both magnitude and phase.

In order to get the describing function for a nonlinearity, the output of this nonlinearity is represented by its Fourier series.

$$f(t) = \frac{A_0}{2} + A_1 \cos \omega t + B_1 \sin \omega t + \dots + A_n \cos n\omega t + B_n \sin n\omega t \quad (3-1)$$

The coefficients of the series are given by

$$A_n = \frac{2}{T} \int_0^T f(t) \cos n \omega t dt \quad (3-2a)$$

$$B_n = \frac{2}{T} \int_0^T f(t) \sin n\omega t dt \quad (3-2b)$$

The definition of the describing function requires that  $A_n$  and  $B_n$  for  $n \geq 2$  are negligible. Thus the coefficients of interest are  $A_1$  and  $B_1$ , and they define the fundamental frequency output as

$$O(t) = |A_1^2 + B_1^2|^{\frac{1}{2}} \underline{\tan^{-1}(A_1/B_1)} \quad (3-3)$$



Then the describing function for the system as illustrated in Figure 3.1 is

$$N = \frac{|A_1^2 + B_1^2|^{\frac{1}{2}}}{B} \frac{\tan^{-1}(A_1/B_1) - \phi}{\quad} \quad (3-6)$$

The above criteria will now be applied to the system under consideration.

A mathematical description of the output wave shape of the nonlinear block must first be obtained for derivation of the describing function. After that the Fourier analysis is worked out to get sinusoidal components of it.

Referring to Figure 3.2, the output of the system has a certain constant speed, and a ripple which is superimposed on this constant level. The first harmonic of the ripple is defined as  $B\sin\omega t$ , and the difference between the constant level and the reference speed as

$$\alpha_0 = V_R - V_{DC}$$

The system is presumed to operate as follows:

a) When the constant level of the speed plus the ripple is less than the reference level the rectifier bridge is "ON" between time a to b, and the output of the nonlinear portion of the system is a three-phase, full-wave rectified voltage of mean value A.

b) At time b where the constant speed plus the ripple equals the reference speed, the rectifier bridge receives an "OFF" signal.



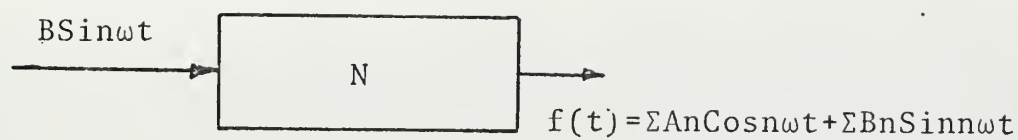


FIGURE 3.1.

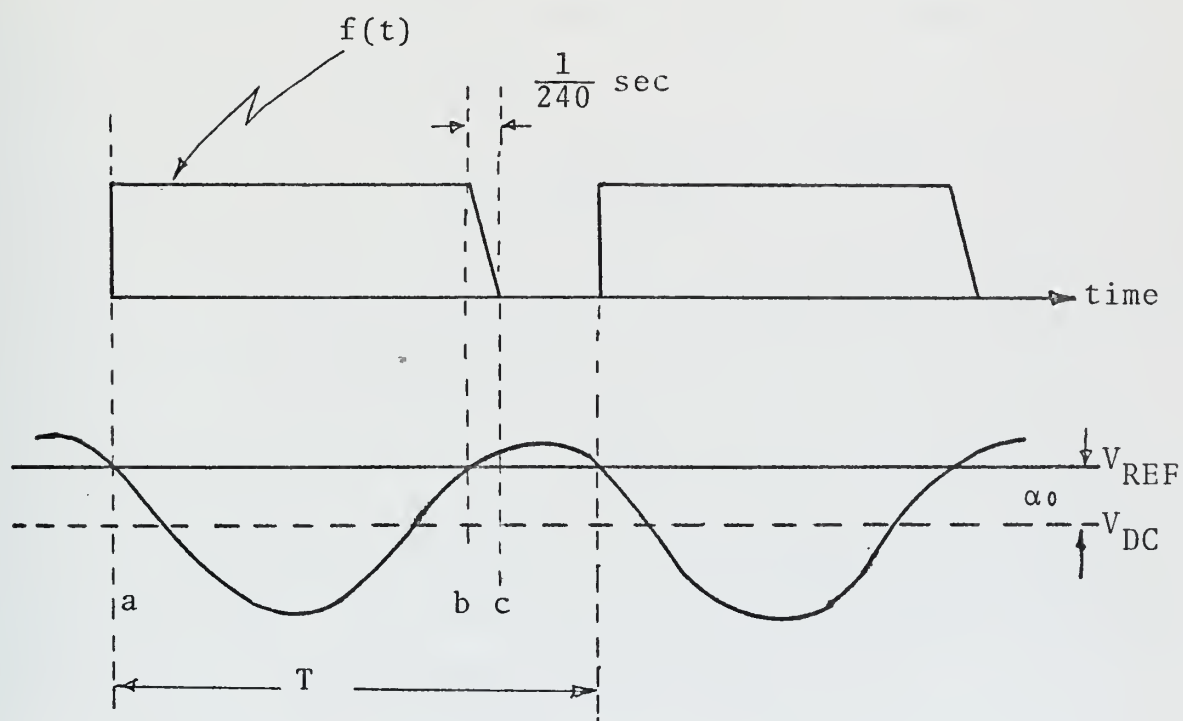


FIGURE 3.2.



c) The rectifier is turned off at time equal to c, a delay of 1/240 second after time b.

d) The rectifier remains off until the output speed again falls below the reference. (Time c to T.) Then the output of the nonlinear block may be summarized as follows:

$$\begin{aligned} f(t) &= 0 & 0 < t < a \\ &= A & a < t < b \\ &= A \frac{c-t}{c-b} & b < t < c \\ &= 0 & c < t < T \end{aligned}$$

The times a, b, and c can be defined in terms of the first harmonic of the ripple.

$$b = \frac{\sin^{-1} \frac{\alpha}{B}}{\omega}$$

$$a = \frac{\pi}{\omega} - b$$

$$c = b + \frac{1}{240}$$

To find the coefficients of the Fourier series equations 3-2a,b are used. The integration must be evaluated over one full cycle of the disturbance frequency, T.

Procedure is as follows:

$$A_n = \frac{2}{T} \int_0^T f(t) \cos n\omega t \, dt$$

$$\frac{c-t}{c-b} = 240b + 1 - 240t$$





Then,

$$A_1 = \frac{2A}{T} \left| \int_a^c \cos \omega t \, dt + 240b \int_b^c \cos \omega t \, dt - 240 \int_b^c t \cos \omega t \, dt \right|$$

Integrating and substituting the limits:

$$A_1 = \frac{2A}{T\omega} \left| \sin \omega c - \sin \omega a + 240b \sin \omega c - 240b \sin \omega b - \frac{240}{\omega} \cos \omega c \right. \\ \left. - 240c \sin \omega c + \frac{240}{\omega} \cos \omega b + 240b \sin \omega b \right|$$

Cancelling terms, the above reduces to:

$$A_1 = \frac{2A}{T\omega} \left| -\sin \omega b + \frac{240}{\omega} (\cos \omega b - \cos \omega c) \right|$$

Using trigonometric identities and substituting the following values,

$$\omega = \frac{T}{2\pi}, \sin \omega b = \frac{\alpha}{B} \text{ and } \cos \omega b = \frac{\sqrt{B^2 - \alpha^2}}{B}$$

The final form of the  $A_1$  term is found as equation 3-5.

$$A_1 = \frac{A}{\pi B} \left| -\alpha + \frac{240}{\omega} \left[ \sqrt{B^2 - \alpha^2} \left( 1 - \cos \frac{\omega}{240} \right) + \alpha \sin \frac{\omega}{240} \right] \right| \quad (3-5)$$

Proceeding in a like manner  $B_1$  is found as equation 3-6.

$$B_1 = \frac{A}{\pi B} \left| -\sqrt{B^2 - \alpha^2} + \frac{240}{\omega} \left[ \alpha \left( 1 - \cos \frac{\omega}{240} \right) - \sqrt{B^2 - \alpha^2} \sin \frac{\omega}{240} \right] \right|$$

(3-6)



The describing function is then:

$$N = \frac{\sqrt{A_1^2 + B_1^2}}{B} \quad / \theta \quad (3-7)$$

where

$$\theta = \tan^{-1}(A_1/B_1)$$

Equations 3-5, 3-6, and 3-7 are suitable for evaluating the numerical value of the describing function. Due to their complex nature, the digital computer was used to overcome the labor required to calculate more than a limited number of points.

The computer program with numerical data is contained in Appendix A.

Since the describing function, which is derived above is dependent upon the frequency, the magnitude of the input,  $B$ , and the difference between constant level of the output and the reference speed  $\alpha_0$ , separate sets of calculations are necessary for each choice of an independent variable. For convenience the magnitude of the input was chosen as the independent variable. The flow chart for the computer program is shown in Figure 3.3.

To make the prediction of limit cycle characteristic the describing functions were drawn on the Nichols chart. They are shown in Figures 3.4 through 3.6.

The values of  $\alpha$  and frequencies for evaluation of describing functions were obtained from the simulation of the system which will be discussed later.



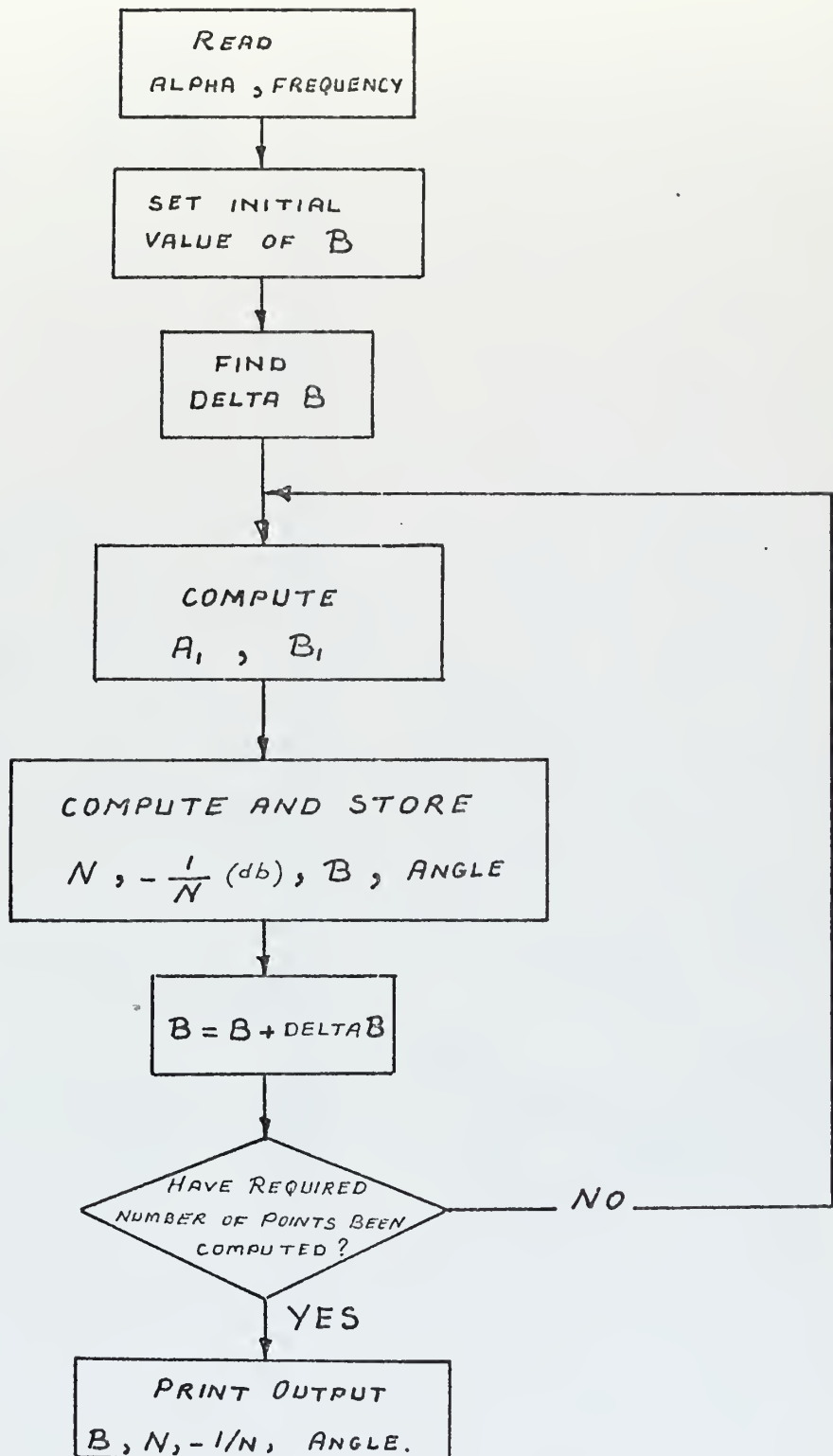


FIGURE 3.3: Flow chart to compute value of describing function.



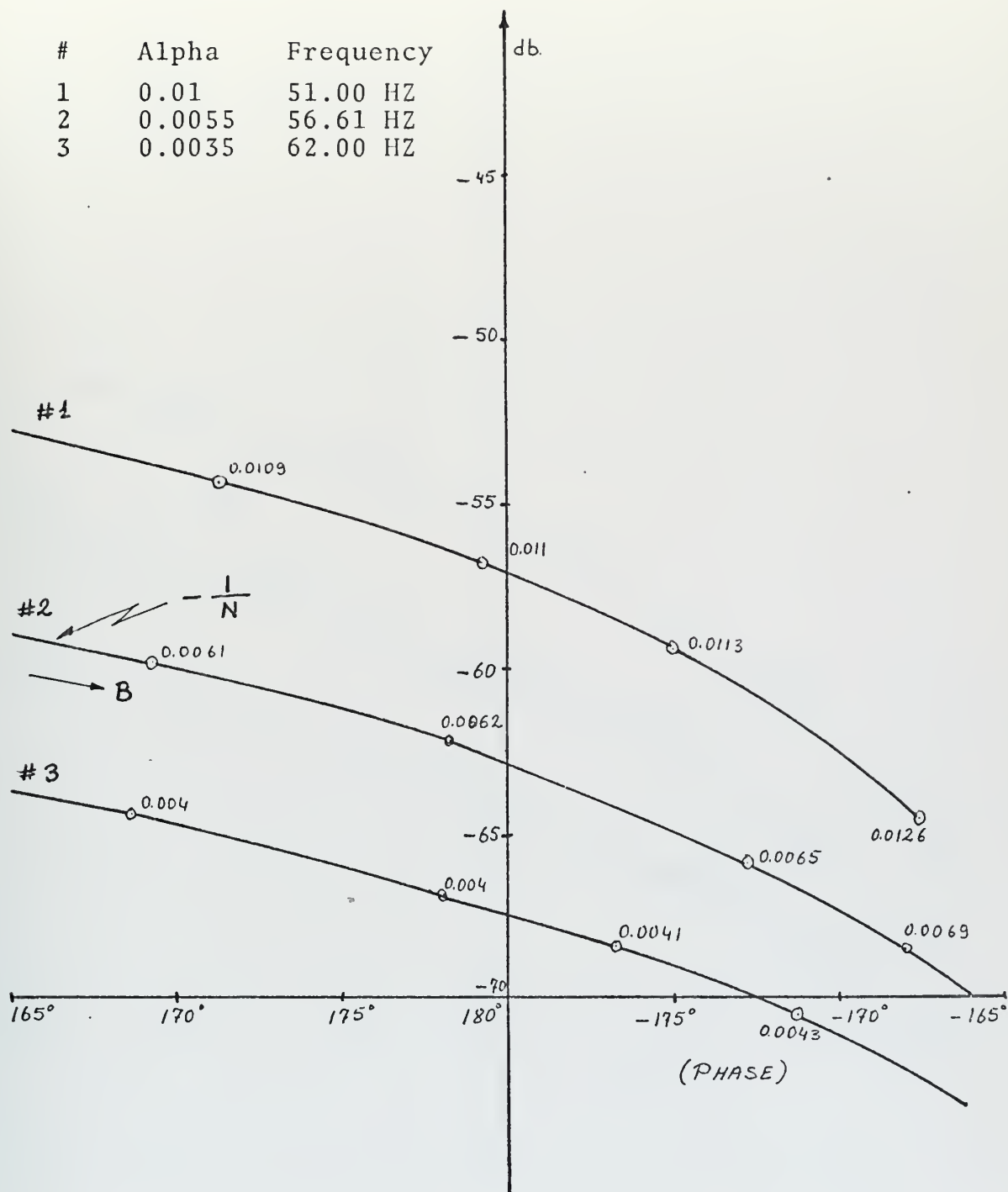


FIGURE 3.4: Describing function  $(-1/N)$  for limit cycling thyristor rectifier bridge.





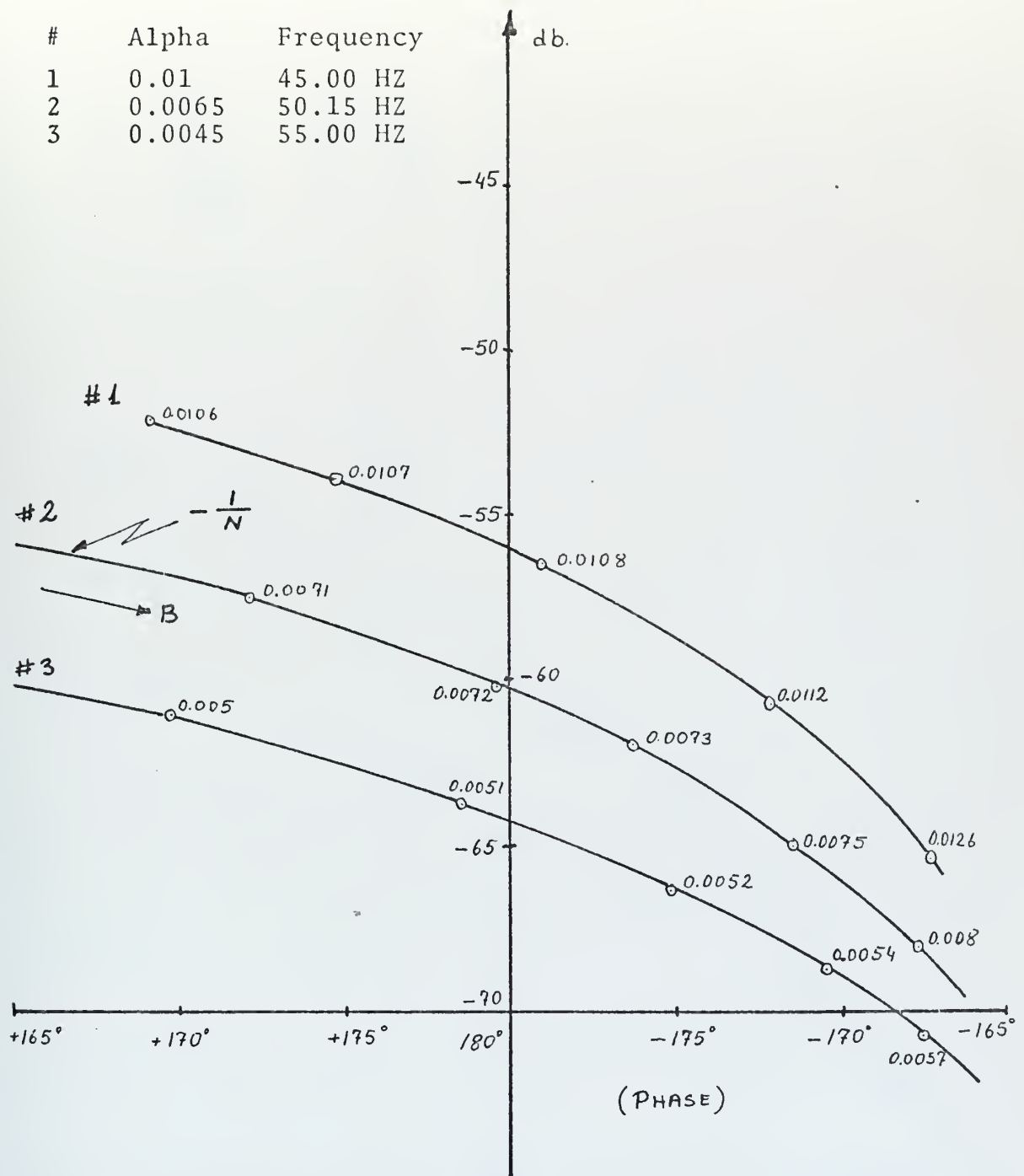


FIGURE 3.5: Describing function  $(-1/N)$  for limit cycling thyristor rectifier bridge.



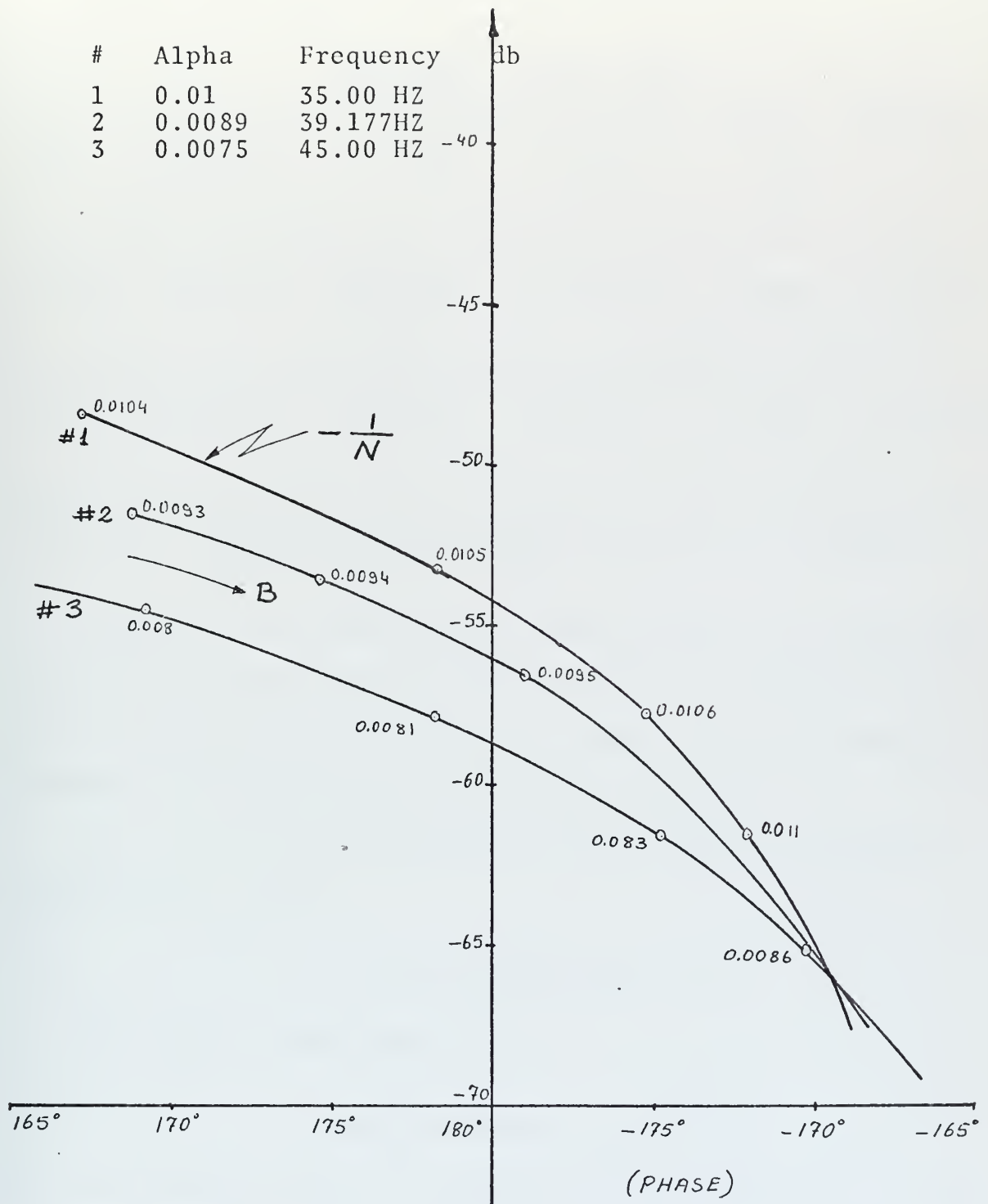


FIGURE 3.6: Describing function  $(-1/N)$  for limit cycling thyristor rectifier bridge.



These values were tabulated in Table 3-1.

$V_r$	$\omega_m$	REFERENCE IN RAD/SEC	MEAN VALUE OF OUTPUT	ALPHA	FREQUENCY
31 <sup>v</sup>	930 rpm	97.4882	97.4843	0.0055	56.61HZ
32.8 <sup>v</sup>	984 rpm	103.1443	103.1378	0.0065	50.15HZ
33.5 <sup>v</sup>	1005 rpm	105.3459	105.337	0.0089	39.177HZ

TABLE 3-1. Tabulation of simulation results for  $V_r$  equal 31, 32.8 and 33.5 Volts.

Having derived the transfer function for the linear portion of the system and describing function for the nonlinear part of the system there are now a number of ways to determine the condition necessary for limit cycling.

The characteristic equation for the system is written from equation 2-3 as:

$$1 + G_1(s) G_2(s) H(s) N = 0$$

This can be rearranged as:

$$G_1(s)G_2(s)H(s) = -\frac{1}{N} = G(s)$$

Thus the intersection of a graphical representation of  $G$  with  $-1/N$  determines the critical point at which limit cycling will occur. Either a Nyquist or a Nichols plot is convenient for this purpose. The choice of the Nichols plot for these analyses is arbitrary.



To determine the location of the limit cycle the describing function curves were superimposed on the frequency response curve of the linear part for frequency 39.177 HZ with alpha 0.0089, for frequency 50.15 HZ with alpha 0.0065, and for frequency 56.61 HZ with alpha 0.0055. The graphs are illustrated in Figures 3.7 through 3.9.

The values of frequency and amplitude were measured at intersections of G with  $-1/N$ . The results are tabulated in Table 3-2.

$V_r$	Amplitude of $-1/N$	Frequency of $-1/N$	Frequency of G
31.	0.0063	56.61 HZ	56.65 HZ
32.8	0.0072	50.15 HZ	50.13 HZ
33.5	0.0095	39.17 HZ	39.23 HZ

TABLE 3-2. Tabulation of the observed limit cycle frequency and amplitude.

From the comparison of the results in Table 3-2, it can be seen that the frequency of the  $-1/N$  curve and frequency of the G curve are very close to each other. This is true for all three cases.

These results were obtained when alpha was equal to the values that are indicated in Table 3-1. Corresponding to these alpha values the amplitude of the limit cycle was found as indicated in Table 3-2.





$$V_R = 31 \text{ Volts}$$

#	Alpha	Frequency
1	0.01	51.00 HZ
2	0.0055	56.61 HZ
3	0.0035	62.00 HZ

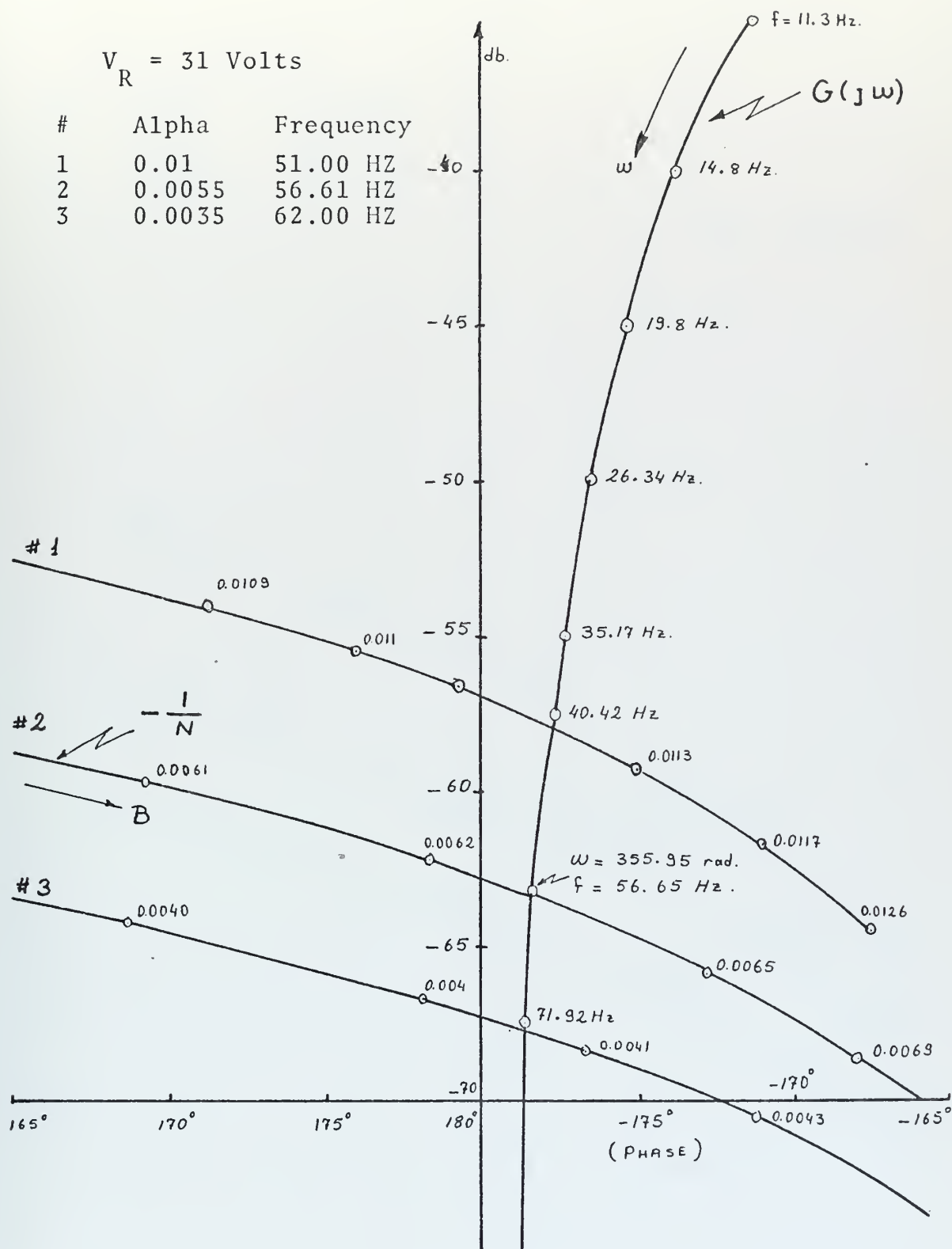


FIGURE 3.7.



$V_R = 32.8$  Volts

#	Alpha	Frequency
1	0.01	45.00 HZ
2	0.0065	50.15 HZ
3	0.0045	55.00 HZ

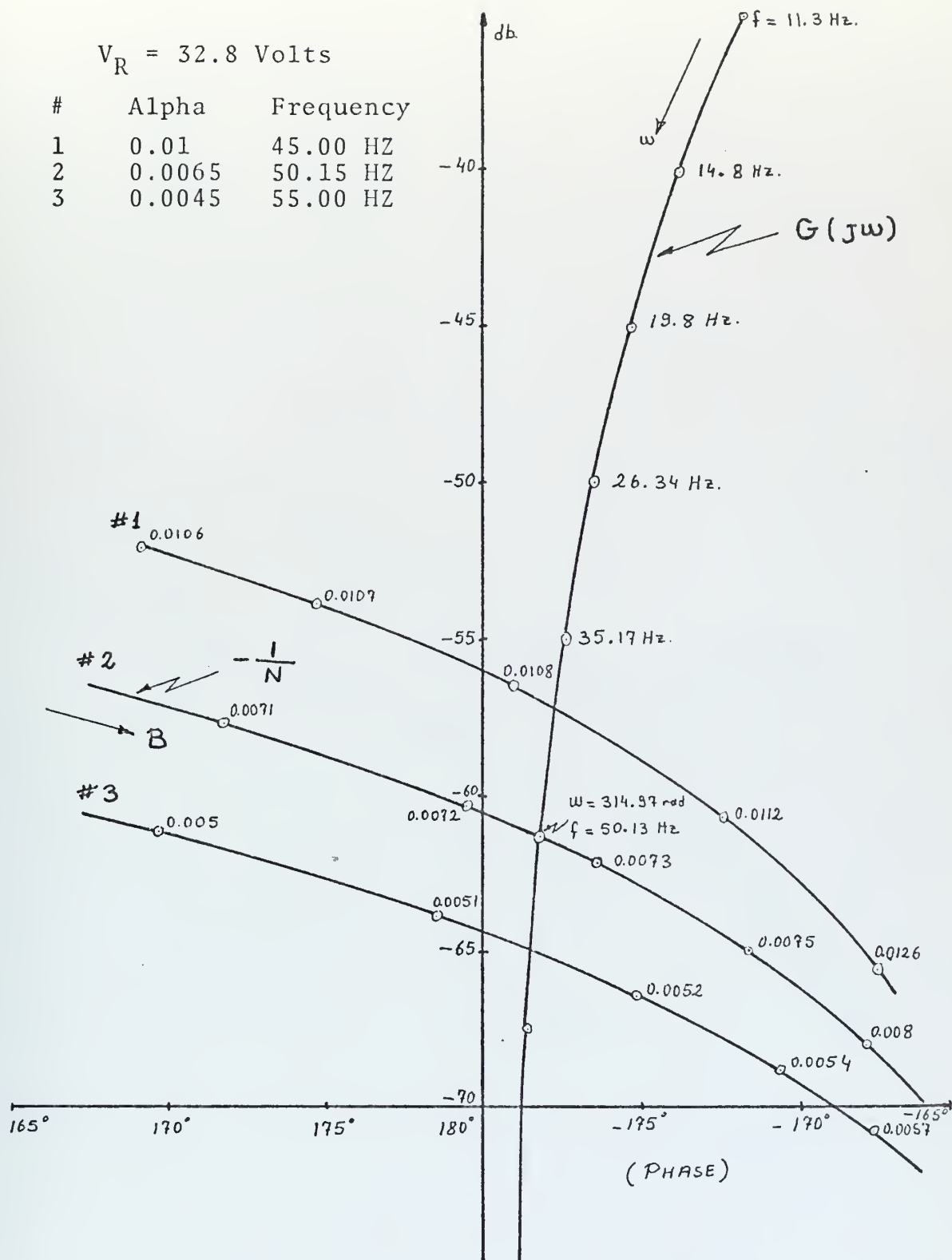


FIGURE 3.8.



$V_R = 33.5$  Volts

#	Alpha	Frequency
1	0.01	35.00 HZ
2	0.0089	39.177HZ
3	0.0075	45.00 HZ

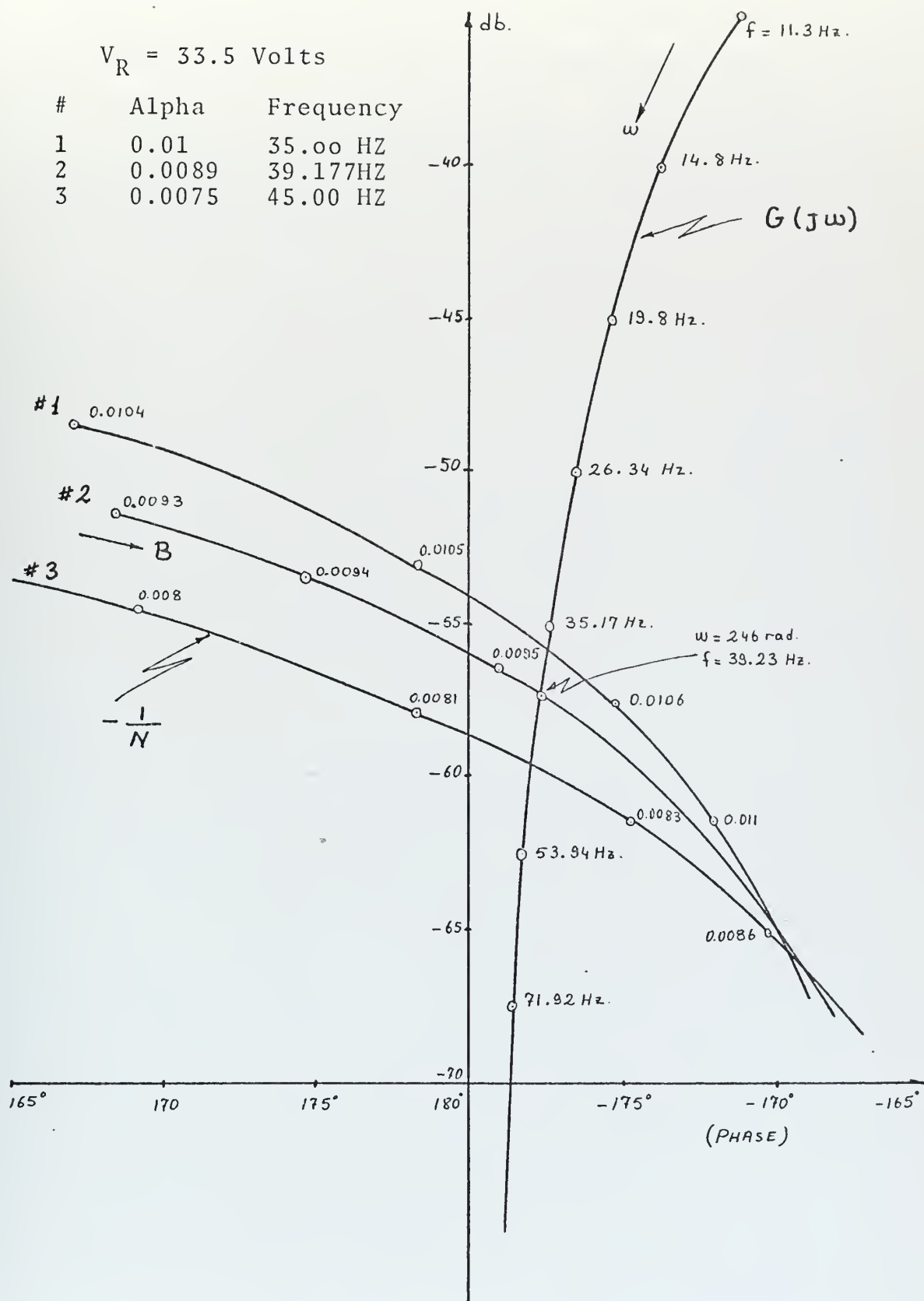


FIGURE 3.9.



Thus there is good agreement with simulation results in both frequencies of the limit cycle and the values of  $\alpha$  predicted by the describing function. This indicates the validity of the describing function in prediction of the limit cycle of the system.





#### IV. SIMULATION OF THE SYSTEM AND SUBHARMONIC EFFECTS

To determine the validity of the describing function and to see the performance of the system in the time domain, the system was simulated on the digital computer. The flow chart for the simulation is shown in Figure 4.1. Naval Postgraduate School computer library subroutine "INTEG 2" was used to solve the differential equations required in the simulation. The complete program is contained in Appendix B.

The supply voltage was considered to be a three-phase 60 cycle A-C source with a peak amplitude of 115 volts throughout the simulation.

The forcing voltage for the system, that is applied to the armature of the D-C motor is a three-phase, full-wave, rectified voltage during time a to b, a portion of a sine wave for the appropriate conduction phase during time b to c, and zero voltage with no reverse current through the inductance during c to T of Figure 3.2.

Graphical output from this program are shown in Figure 4.2 illustrating the input voltage wave form, and Figures 4.3 through 4.7 illustrating the output speed wave forms.

Simulation was performed by changing the reference from 930 r.p.m. to 1260 r.p.m. These are shown in Table 4-1.

When a linear system is driven with a sinusoidal input it is known that the steady state output is also a sinusoid, differing from the input in amplitude and phase but having precisely the same frequency. For linear systems, that is



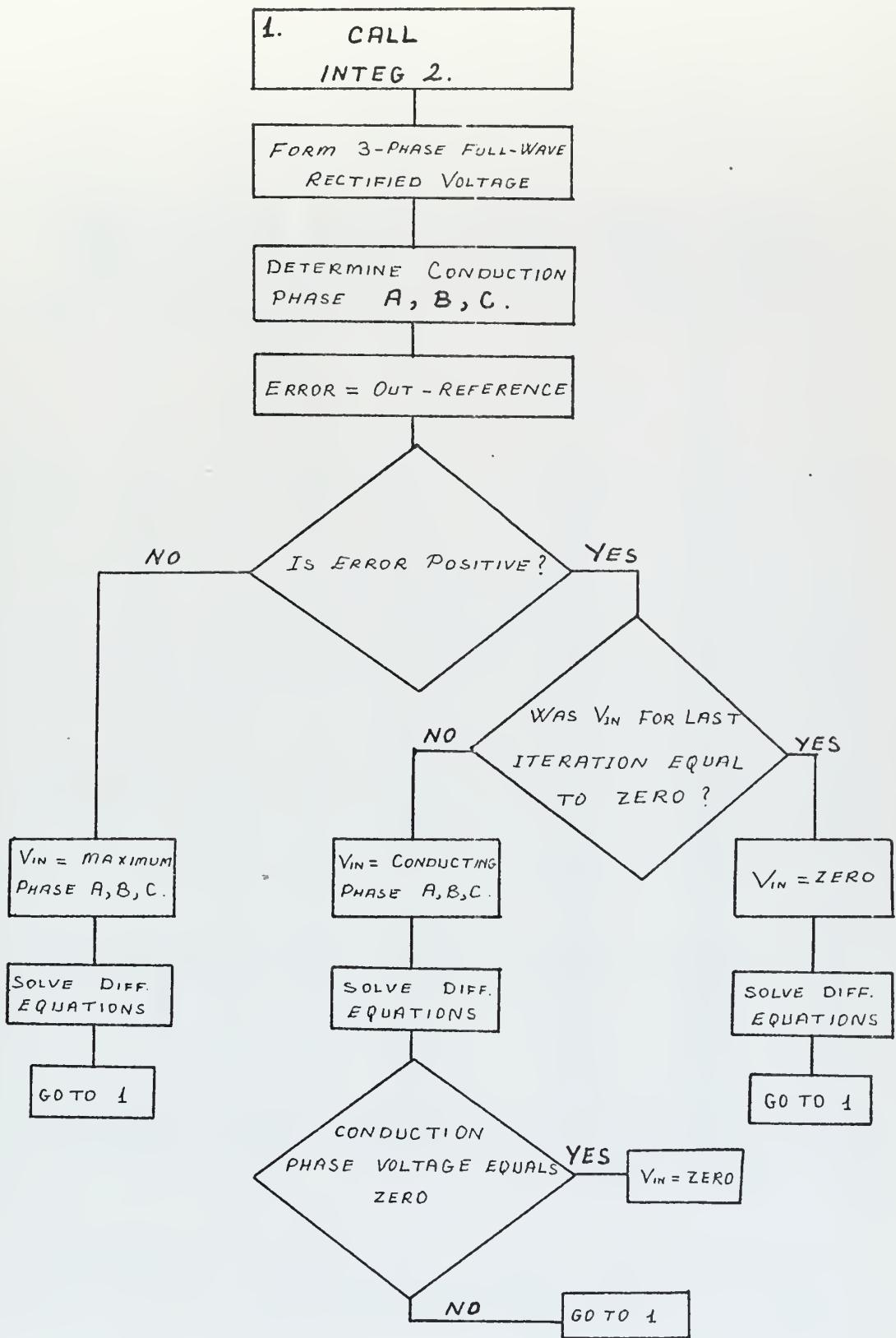
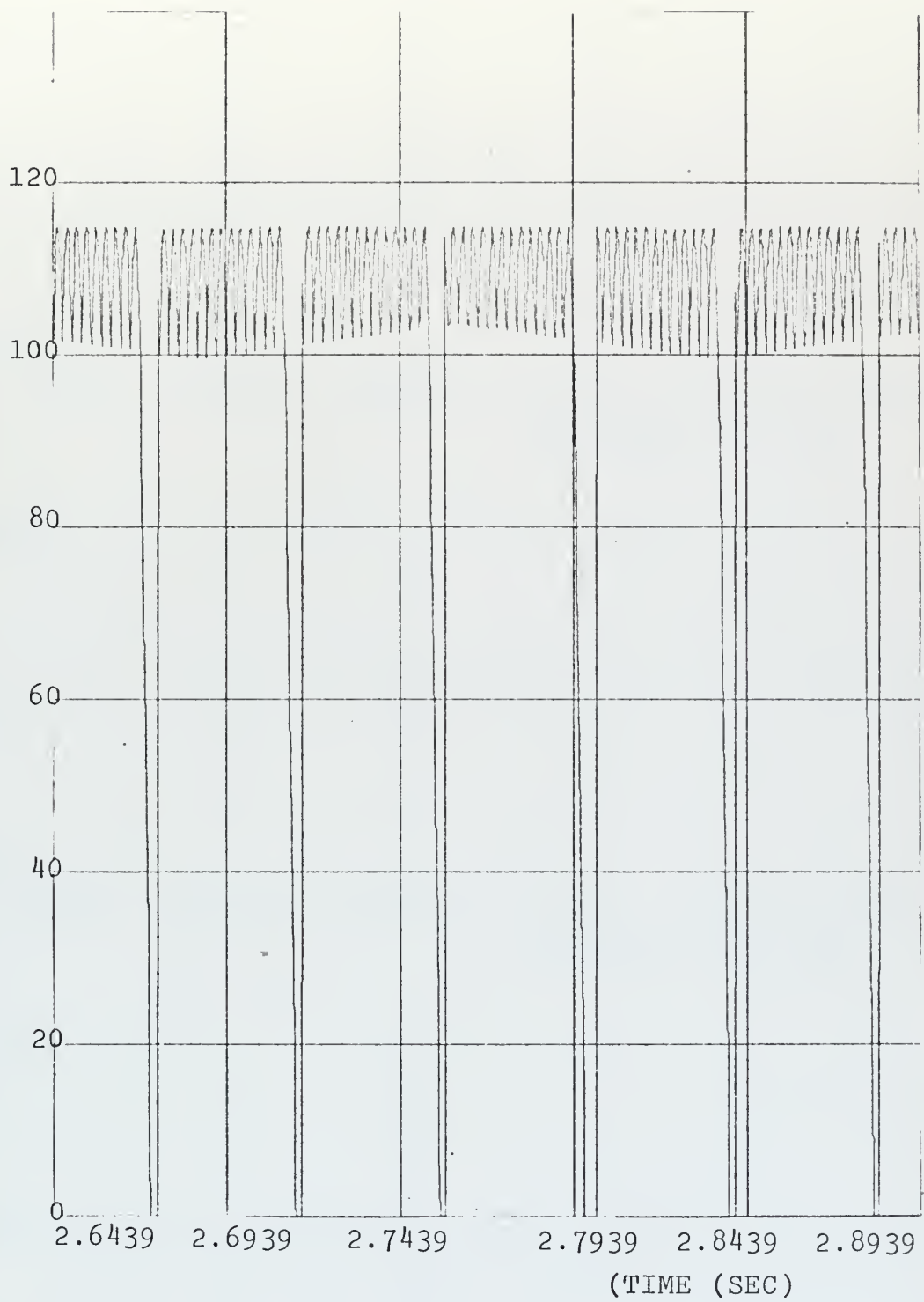


FIGURE 4.1. Flow chart for simulation.





. FIGURE 4-2. Simulation results, input voltage.  
Reference speed 1050 rpm.



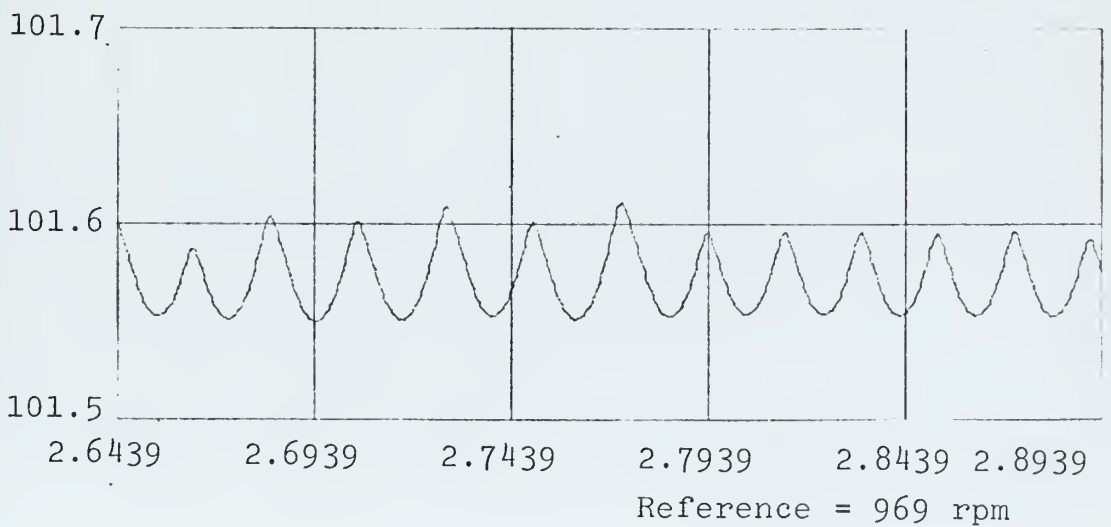
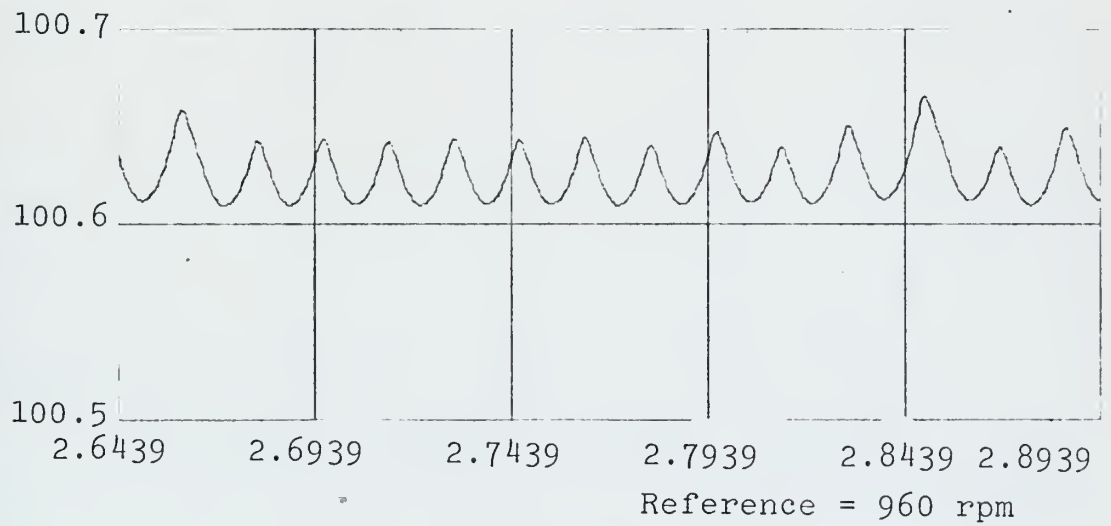
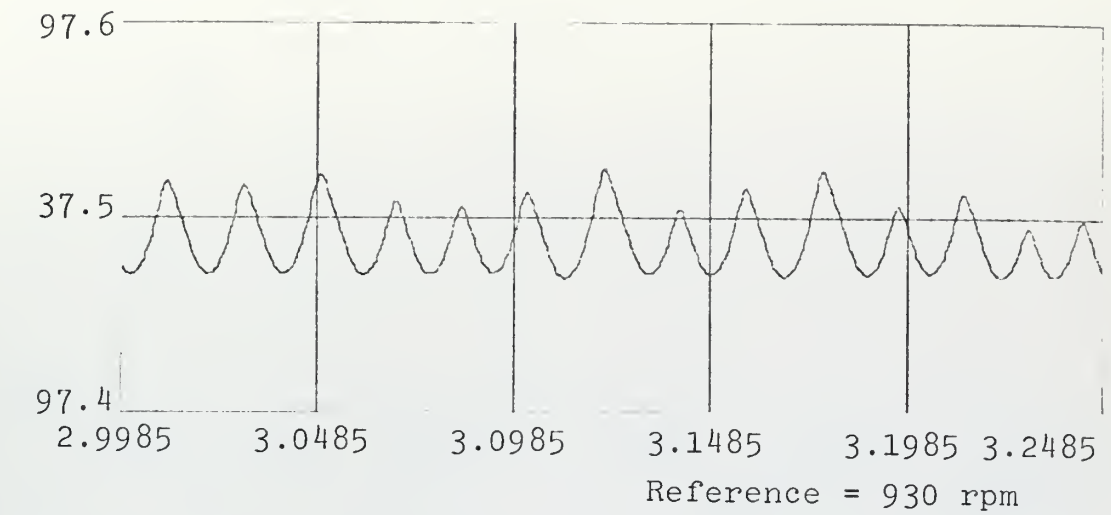


FIGURE 4-3. Simulation results, output speed.





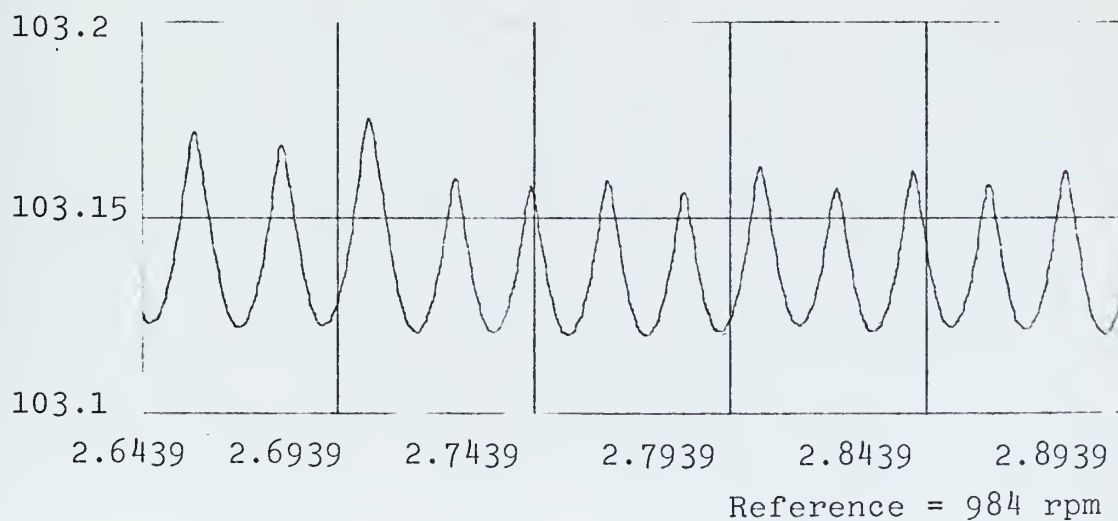
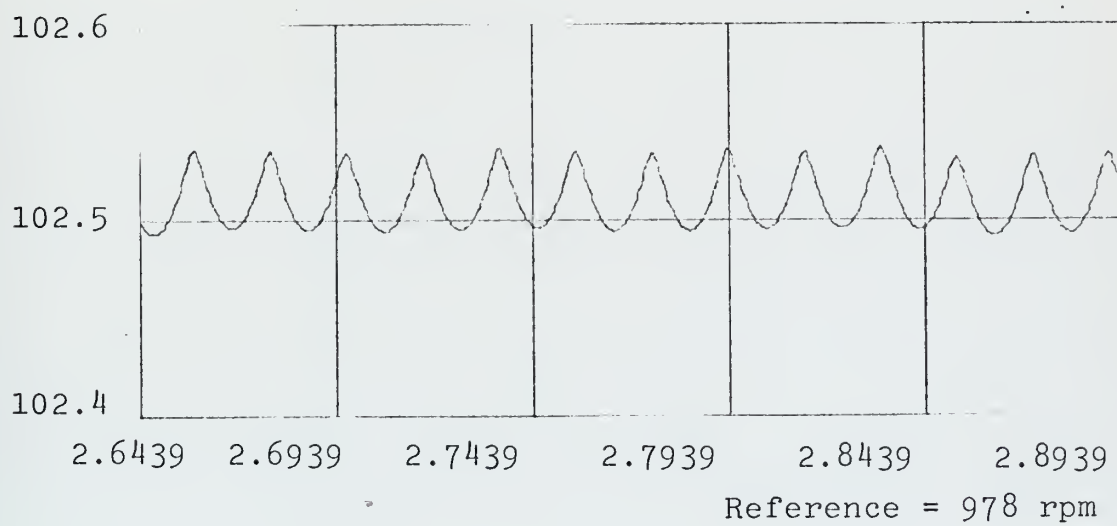
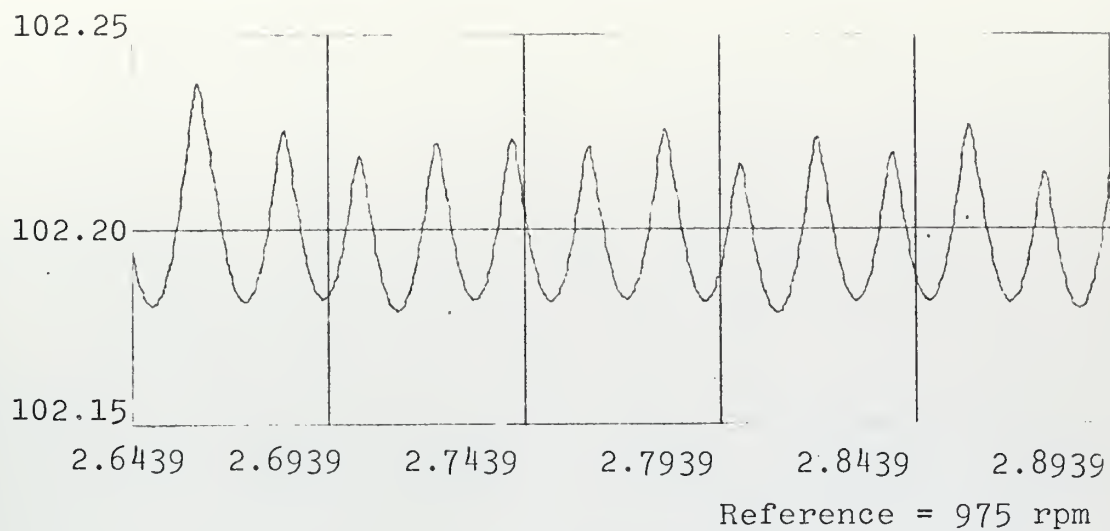


FIGURE 4-4. Simulation results, output speed



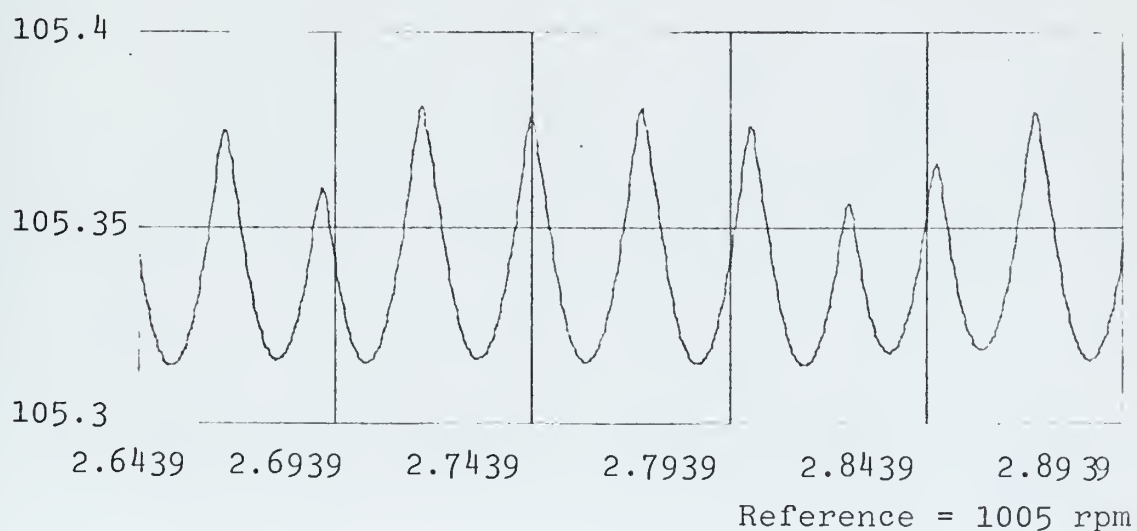
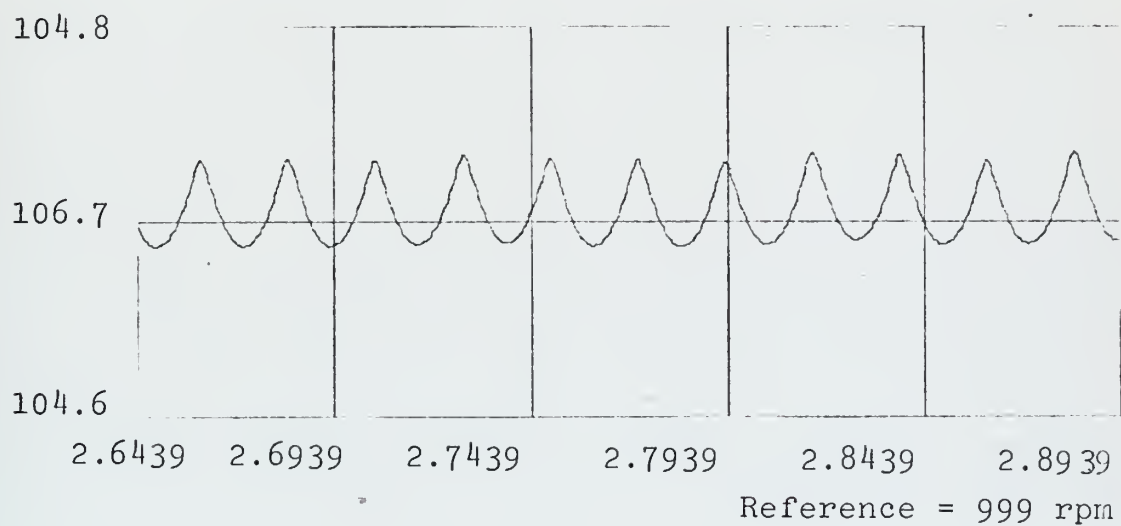
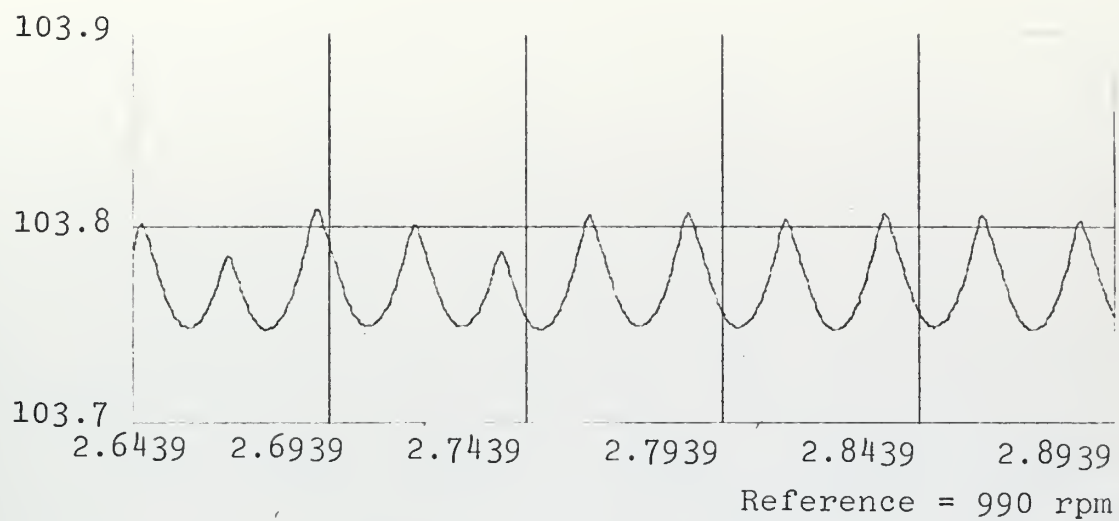


FIGURE 4-5. Simulation results, output speed.



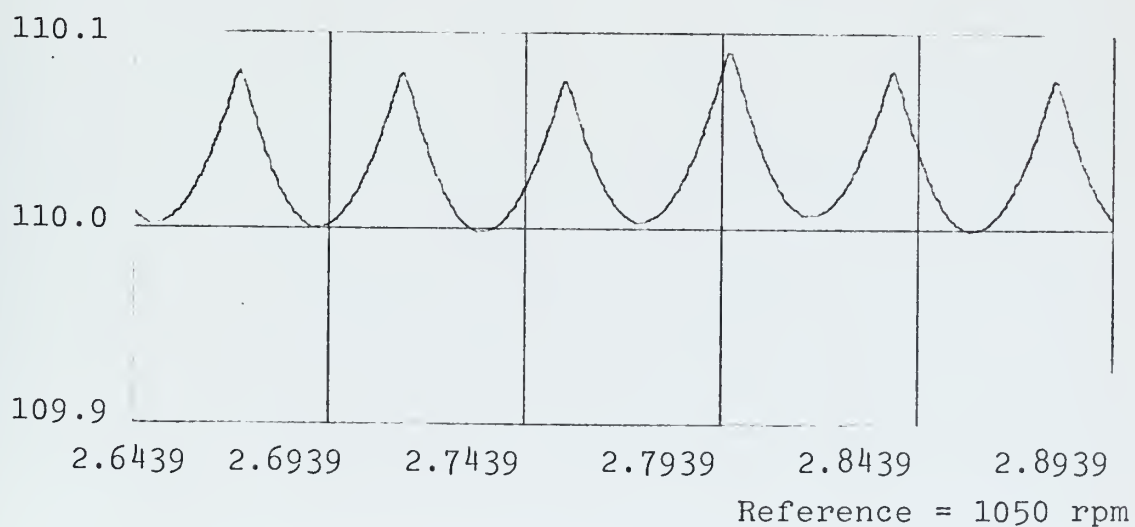
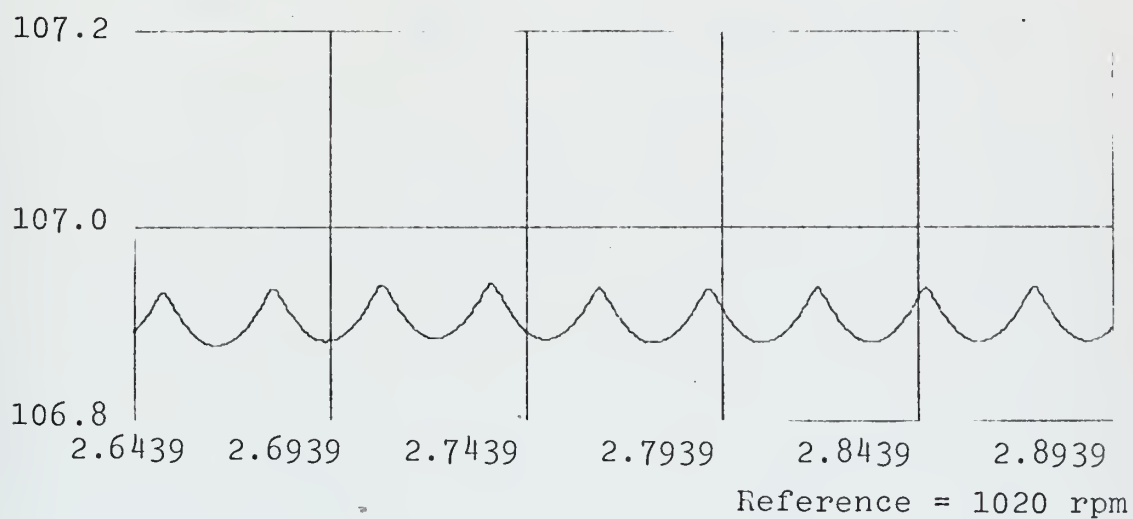
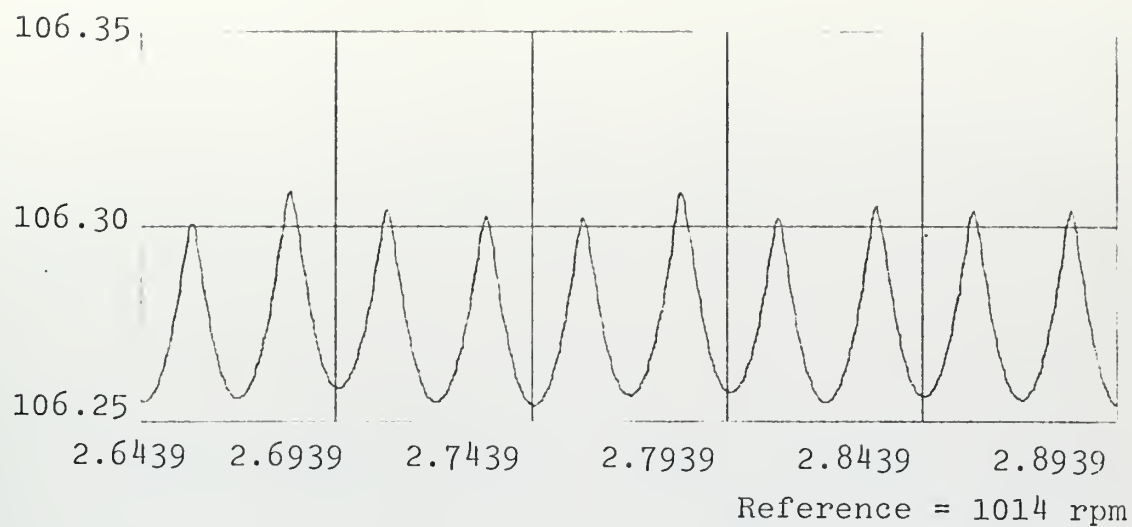


FIGURE 4-6. Simulation results, output speed.



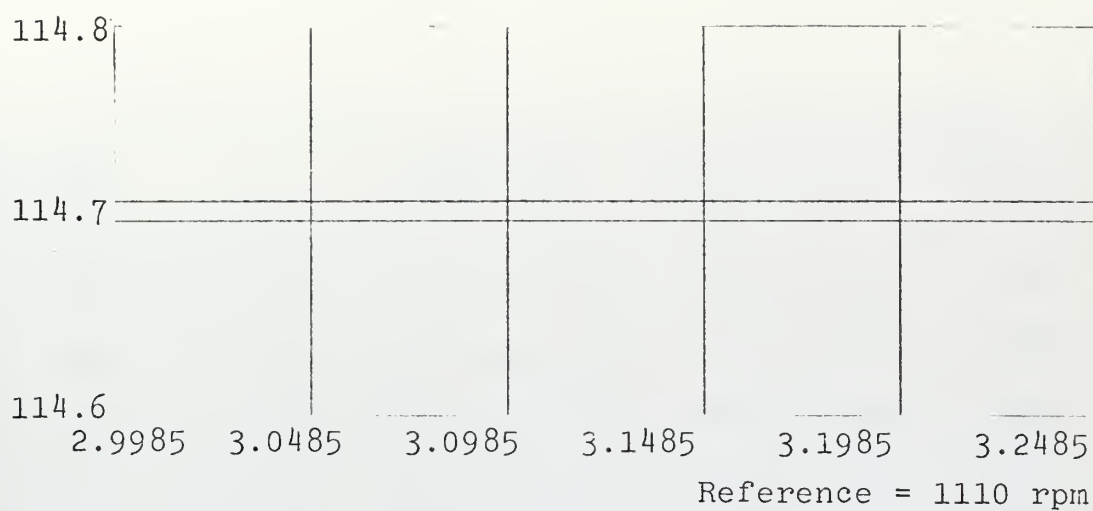


FIGURE 4-7. Simulation results, output speed.





REFERENCE VOLTAGE		SPEED	PERIOD OF LIMIT CYCLE	FREQUENCY OF LIMIT CYCLE	DOES SUB- HARMONIC EXIST?
31	volt	930 rpm	0.017663 Sec	56.61 HZ	YES
32	volt	960 rpm	0.017631 Sec	56.71 HZ	YES
32.3	volt	969 rpm	0.021173 Sec	47.28 HZ	YES
32.5	volt	975 rpm	0.019924 Sec	50.14 HZ	YES
32.6	volt	978 rpm	0.0195 Sec	51.28 HZ	YES
32.8	volt	984 rpm	0.01994 Sec	50.13 HZ	YES
33.	volt	990 rpm	0.02391 Sec	41.82 HZ	YES
33.3	volt	999 rpm	0.0223 Sec	44.576 HZ	YES
33.5	volt	1005 rpm	0.025525 Sec	39.177 HZ	YES
33.8	volt	1014 rpm	0.02545 Sec	39.293 HZ	YES
34.	volt	1020 rpm	0.027838 Sec	35.923 HZ	YES
35.	volt	1050 rpm	0.0394 Sec	25.4 HZ	YES
37.	volt	1110 rpm	NO	LIMIT	CYCLE
40.	volt	1200 rpm	NO	LIMIT	CYCLE
42.	volt	1260 rpm	NO	LIMIT	CYCLE

TABLE 4-1. Tabulation of simulation results.



true at all frequencies. In the case of a nonlinear system a sinusoidal input does not guarantee an output which is a sinusoid. In the usual case, the output wave contains harmonic frequency components which are integral multiples of the forcing frequency. In some cases, the output wave may contain one or more frequencies which are lower than the forcing frequency. Characteristically, these frequencies are integral submultiples of the forcing frequency which are called subharmonic frequencies. The amplitude of the subharmonic component may be small compared with the amplitude of the component at the driving frequency, or it may be so large that the driving frequency may be neglected for particular computations.

If the output wave shapes in Figure 4.3 through 4.7 are inspected, it is observed that the wave forms have a ripple instability which is small in amplitude compared to the average ripple amplitude. One can think this instability is caused by subharmonic effects of the system. It can be observed by inspection, but it is not possible to obtain its frequency and its amplitude from the output wave shapes, because they do not have a regular pattern. To figure out this instability, the Fourier analysis of the output wave shapes for reference speed 930, 984, and 1005 r.p.m. were made. During the Fourier analysis, several limit cycle periods were taken as a fundamental period of the Fourier, then the same harmonics of these fundamental frequencies which are also subharmonics of the limit cycle were obtained. From these results, amplitude and the order of subharmonic components of



the limit cycle in the output wave were calculated. These were tabulated in Table 4-2 through 4-4.

In Figure 4.8 through 4.10, the amplitude of the subharmonics was drawn to see the relative heights of the components. In Figure 4.8, it is seen that, at reference speed 930 r.p.m.  $1/8$  and  $1/16$  subharmonics have larger amplitude compared to others. Their amplitudes are approximately 15.6 percent of the output ripple amplitude. In Figure 4.9 which was drawn for reference speed 984 r.p.m.,  $1/2$  subharmonic has larger amplitude and it is equal 25.3 percent of the output ripple. In Figure 4.10, which is for reference speed 1005 r.p.m. the largest subharmonic is  $1/7$ . It has amplitude 16.1 percent of the ripple amplitude.



LIMIT CYCLE AMPLITUDE	ORDER OF SUBHARMONIC # OF CYCLE	1/2	1/3	1/4	1/5	1/6	1/7	1/8	1/16
0.01982	4	0.00314		0.00323					
0.01786	8	0.00104		0.00086				0.00282	
0.01872	12	0.00093	0.00273	0.00117		0.00105			
0.01871	14	0.00074					0.00176		
0.01296	16	0.00063		0.00146				0.00290	0.00237
0.01231	18	0.00171	0.00207			0.00081			
0.01135	20	0.00205		0.00136	0.00183				
0.00882	24	0.00145	0.00130	0.00066		0.00107		0.00130	
0.01507	Average	0.00146	0.00203	0.00145	0.00183	0.00098	0.00176	0.00234	0.00237

TABLE 4-2: Tabulation of Fourier analysis for  $V_R = 31$  Volts.





LIMIT CYCLE AMPLITUDE	ORDER OF SUBHARMONIC # OF CYCLE		1/2	1/3	1/4	1/5	1/6	1/7	1/8	1/16
0.01803	4	0.00830			0.00279					
0.01807	8	0.00516			0.00302				0.00065	
0.01626	12	0.00406	0.00099	0.00230			0.00148			
0.01576	14	0.00296						0.00017		
0.01526	16	0.00179		0.00160					0.00100	0.00197
0.01456	18	0.00256	0.00039				0.00148			
0.01276	20	0.00326			0.00182	0.00029				
0.01648	24	0.00388	0.00050	0.00065			0.00125		0.00062	
0.01590	Average	0.00407	0.00063	0.00203	0.00029	0.00140	0.00017	0.00076	0.00197	

TABLE 4-3: Tabulation of Fourier analysis for  $V_R = 32.8$  Volts.



LIMIT CYCLE AMPLITUDE	ORDER OF SUBHARMONIC	1/2	1/3	1/4	1/5	1/6	1/7	1/8	1/16
	# OF CYCLE								
0.02045	4	0.00359		0.00343					
0.02180	8	0.00162		0.00427				0.00132	
0.01901	12	0.00274	0.00242	0.00187		0.00309			
0.01944	14	0.00212					0.00326		
0.02020	16	0.00252		0.00273				0.00232	0.00146
0.02015	18	0.00172	0.00298			0.00279			
0.02150	20	0.00152		0.00286	0.00116				
0.01944	24	0.00175	0.00262	0.00226		0.00146		0.00231	
0.02025	Average	0.00220	0.00267	0.00290	0.00116	0.00245	0.00326	0.00199	0.00146

TABLE 4-4: Tabulation of Fourier analysis for  $V_R = 33.5$  Volts.



L.C. Frequency = 56.61 HZ  
 SPEED = 930 r.p.m.

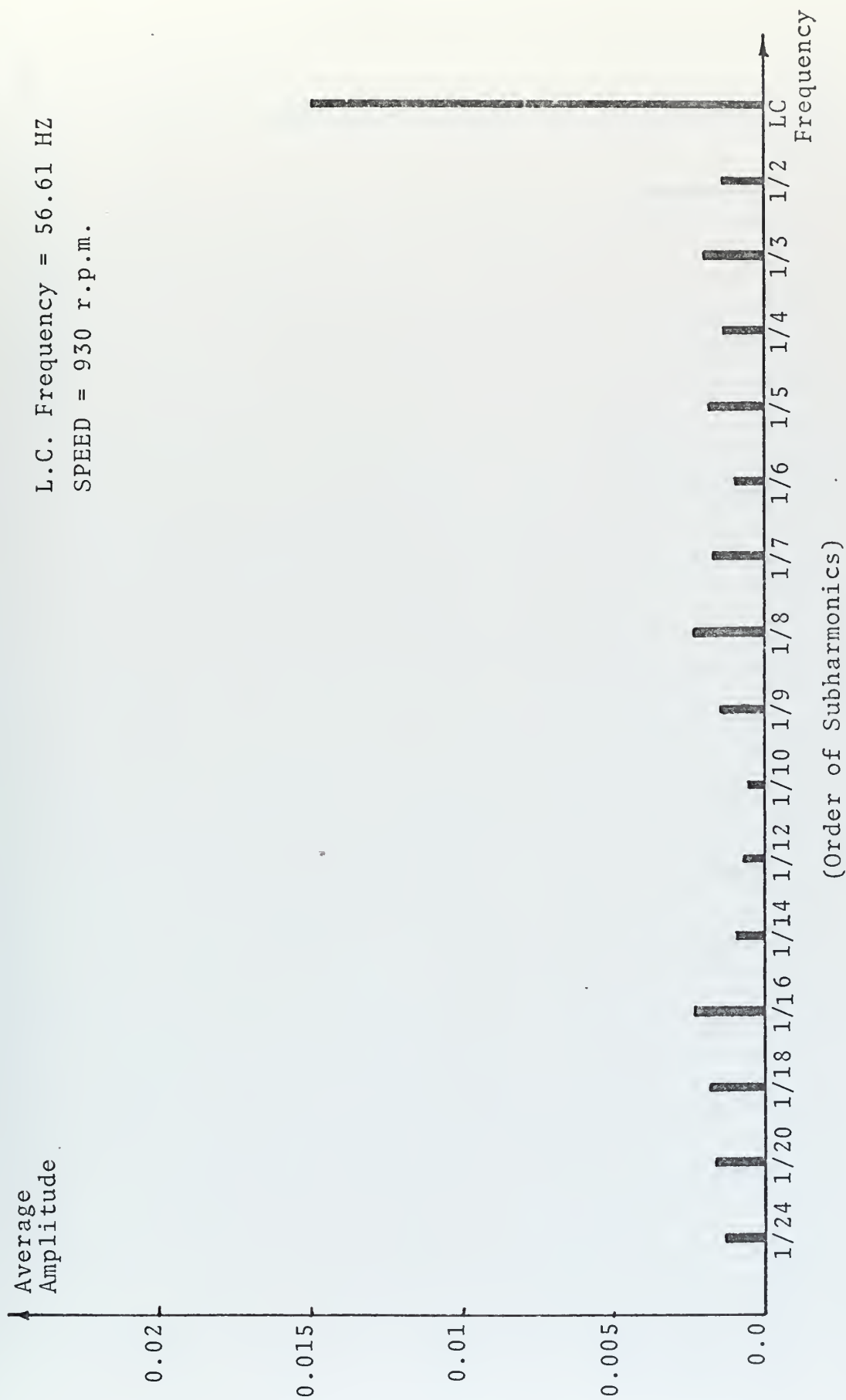


FIGURE 4.8: Average amplitudes of the subharmonics for  $V_R = 31$  Volts.



L.C. Frequency = 50.15 HZ  
 Speed = 984 r.p.m.

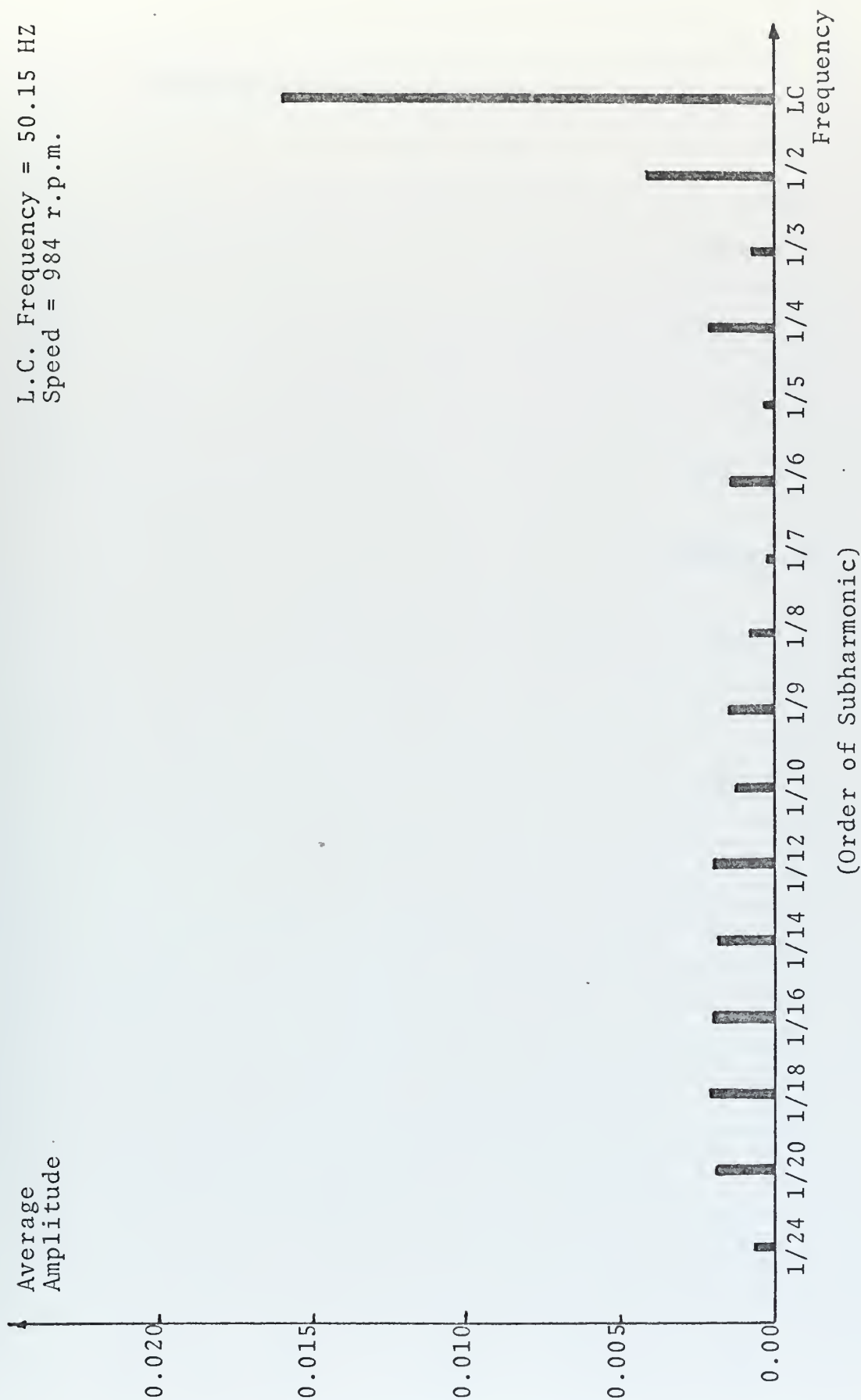


FIGURE 4.9: Average amplitude of the subharmonics for  $V_R = 52.8$  Volts.





L.C. Frequency = 39.177 HZ  
 Speed = 1005 r.p.m.

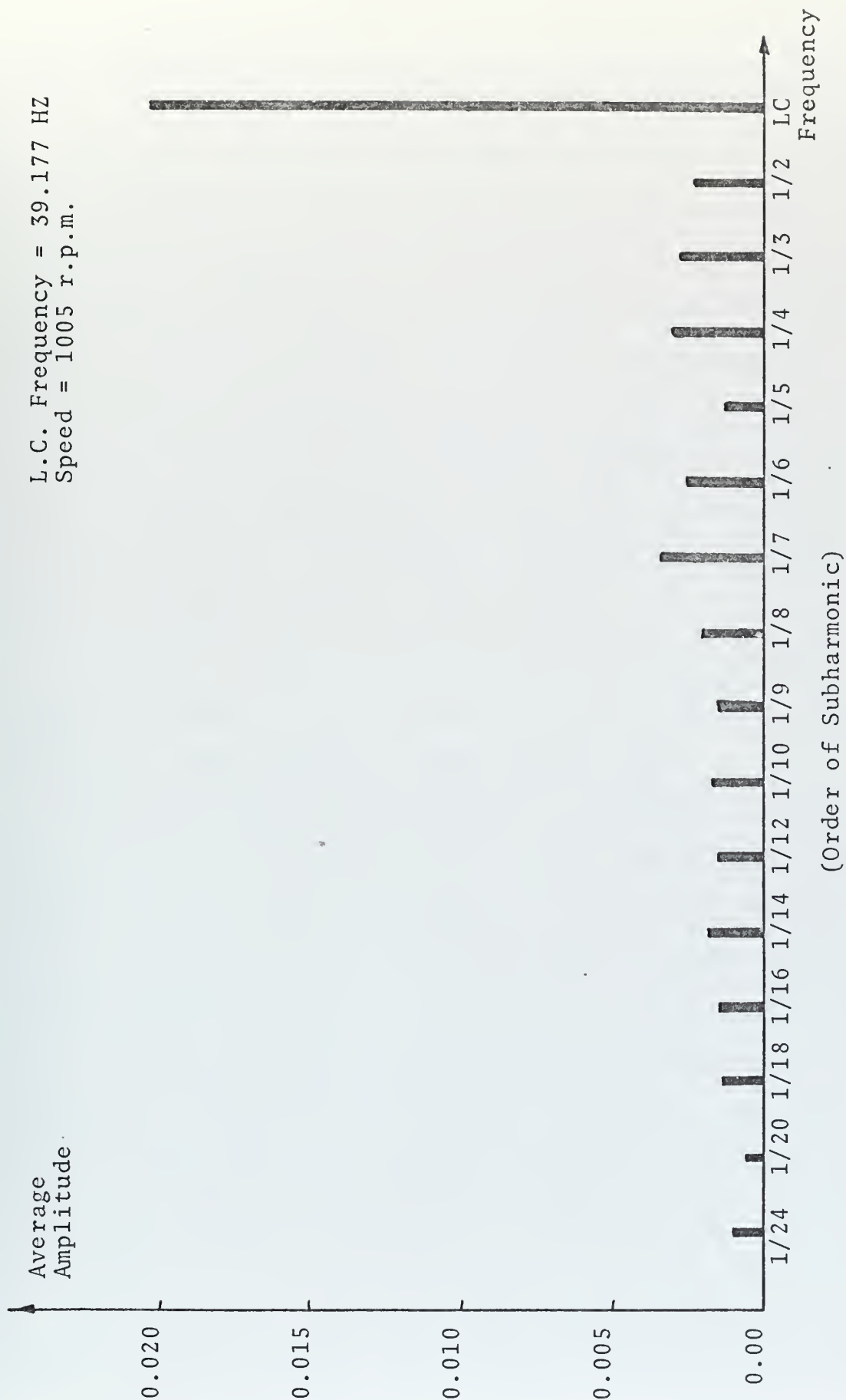


FIGURE 4.10: Average amplitudes of the subharmonics for  $V_R = 33.5$  Volts.



## V. CONCLUSION AND RECOMMENDATION FOR FURTHER STUDY

The main conclusion that might be reached in reviewing the experimental results is that the D-C motor at constant field current operates at an almost constant speed, and its speed may be controlled over wide ranges by armature-voltage control. This can be seen from Figures 4.3 through 4.7. If these figures are inspected closely it can be observed that the ripple amplitudes are very small compared to the output value. They are approximately within the  $\pm 0.025$  percent of the desired value of the output. This may be acceptable for most of the applications in the industry.

Armature-voltage control was performed by adjusting the conduction phase of the thyristor-rectifier bridge. This causes the limit cycling in the control loop.

The describing function derived in Chapter III provides a mean by which the nonlinearity of the system can be represented and the overall performance of the system analyzed. It is possible to predict the approximate frequency and amplitude of the limit cycle as illustrated in Figures 3.7 through 3.9. In order to predict the response more precisely, it is necessary to predetermine the value of  $\alpha$ , that might be done by simulating the system and measuring the output mean value then taking the difference between output mean value and reference.

One tentative conclusion that can be achieved by examination of the experimental data is that, under certain conditions



the forced-limit-cycling speed control system will have subharmonic ripple instability.

The describing function derived accounts only for the first harmonic of the output voltage from the nonlinear portion of the system and assumes that higher harmonics are negligible. However, as seen in Figures 4.3 through 4.7 the other harmonics can exist. In some cases these harmonics can be submultiples of the limit cycle frequency.

In this study Fourier analysis was performed to see whether the subharmonic exists or not. As a result Tables 4-2 through 4-4 and Figures 4.8 through 4.10 were obtained. These show that the ripple instability is caused by subharmonic effects of the system nonlinearity. But this is not good enough to predict the existence of the subharmonic in the output of the system. It can give some insight about the nature of the problem. There are no general rules available which define the conditions necessary for the occurrence of the subharmonic oscillation. For mathematical analysis several of the references noted in the List of References suggest that a possible method of prediction of the subharmonic ripple instability in the system would be to employ a Dual Input Describing Function. Any further study should give some consideration to these analytical methods to understand ripple instability and existence of the subharmonic.

Another area for study is to increase the gain and see the effect of the gain on the ripple instability. This may require some sort of compensation network to eliminate the instability in the output for a range of gain values.



## APPENDIX A

Computer program for computing value of describing curves. Numerical data for  $-1/N$  curves plotted in Figure 3.4 through 3.9.





```

DIMENSION X(1500),Y(1500),Z(1500),YY(1500)
PI=3.141592
FREQ=45.0
ALPHA=0.01
C5=ALPHA
T=1.0/FREQ
XPHI=3.0*FREQ/(4.0*57.29578)
XLAN=C5*((1.1/COS(XPHI))-1.0)
XINC=XLAN/50.0
B=C5+XINC
C3=PI/(120.0*T)
DO 200 J=1,50
  NPT=J
  NJ=J
  C1=1.0/(B*PI)
  DOG=B**2-C5**2
  IF(DOG)300,300,301
300  C2=0.0
  GO TO 302
301  C2=SQRT(DOG)
302  CONTINUE
  A1=C1*(-C5+(1.0/C3)*(C2-C2*COS(C3)+C5*SIN(C3)))
  B1=C1*(-C2+(1.0/C3)*(C5*(1.0-COS(C3))-C2*SIN(C3)))
  X(J)=B
  Y(J)=(SQRT(A1**2+B1**2))*110.0/B
  Z(J)=57.29578*ATAN2(A1,B1)
  YY(J)=20.0*(ALOG10(Y(J)))
  Z(J)=-Z(J)
  YY(J)=-YY(J)
  B=B+XINC
200  CONTINUE
  WRITE(6,101)
101  FORMAT(1H1,/,T24,'DESCRIBING FUNCTION DATA',/)
  WRITE(6,401) FREQ
401  FORMAT(T24,'FREQUENCY = ',F6.3,/)
  WRITE(6,402) ALPHA
402  FORMAT(T24,'ALPHA = ',F6.4,/)
  WRITE(6,107)
107  FORMAT(1H1,/,T31,'N',T42,'PHASE',T56,'-1/N(DB)',/)
  DO 201 J=1,50
201  WRITE(6,102) X(J),Y(J),Z(J),YY(J)
102  FORMAT(14X,F6.4,6X,F9.4,6X,F7.2,6X,F8.4)
  CONTINUE
  STOP
  END

```



# DESCRIBING FUNCTION DATA

FREQUENCY = 51.000

ALPHA = 0.0100

B	N	PHASE	-1/N(DB)
0.0101	1401.8879	29.27	-62.9343
0.0102	1060.7751	32.61	-60.5125
0.0102	805.8579	36.95	-58.1252
0.0103	600.5212	43.26	-55.5706
0.0104	433.9397	53.37	-52.7486
0.0105	308.9268	70.87	-49.7971
0.0106	244.2780	99.49	-47.7577
0.0106	257.4648	130.96	-48.2144
0.0107	324.0369	152.10	-50.2119
0.0108	410.2649	164.16	-52.2613
0.0109	500.6140	171.37	-53.9901
0.0110	589.5430	176.04	-55.4103
0.0110	675.1055	179.29	-56.5874
0.0111	756.6646	-178.34	-57.5781
0.0112	834.0947	-176.53	-58.4243
0.0113	907.4871	-175.10	-59.1568
0.0114	977.0127	-173.95	-59.7980
0.0114	1042.8850	-172.99	-60.3647
0.0115	1105.3154	-172.19	-60.8697
0.0116	1164.5139	-171.51	-61.3229
0.0117	1220.6768	-170.92	-61.7320
0.0118	1273.9927	-170.41	-62.1033
0.0118	1324.6333	-169.95	-62.4419
0.0119	1372.7588	-169.55	-62.7519
0.0120	1418.5159	-169.19	-63.0367
0.0121	1462.0398	-168.87	-63.2992
0.0122	1503.4609	-168.57	-63.5418
0.0122	1542.8931	-168.31	-63.7667
0.0123	1580.4492	-168.06	-63.9756
0.0124	1616.2246	-167.84	-64.1700
0.0125	1650.3162	-167.63	-64.3513
0.0126	1682.8105	-167.44	-64.5207
0.0126	1713.7903	-167.26	-64.6791
0.0127	1743.3315	-167.10	-64.8276
0.0128	1771.5032	-166.94	-64.9668
0.0129	1798.3711	-166.80	-65.0976
0.0130	1824.0007	-166.66	-65.2205
0.0130	1848.4512	-166.53	-65.3362
0.0131	1871.7751	-166.41	-65.4451
0.0132	1894.0234	-166.30	-65.5477
0.0133	1915.2488	-166.19	-65.6445
0.0134	1935.4958	-166.09	-65.7358
0.0134	1954.8059	-165.99	-65.8221
0.0135	1973.2205	-165.90	-65.9035
0.0136	1990.7820	-165.81	-65.9805
0.0137	2007.5239	-165.73	-66.0532
0.0138	2023.4832	-165.65	-66.1220
0.0138	2038.6892	-165.57	-66.1870
0.0139	2053.1780	-165.50	-66.2485
0.0140	2066.9778	-165.43	-66.3067



# DESCRIBING FUNCTION DATA

FREQUENCY = 56.610

ALPHA = 0.0055

B	N	PHASE	-1/N(DB)
0.0056	2811.1938	32.44	-68.9778
0.0056	2136.1204	36.08	-66.5925
0.0057	1634.1643	40.74	-64.2659
0.0057	1233.0056	47.36	-61.8193
0.0058	911.0759	57.52	-59.1911
0.0058	671.7336	74.02	-56.5439
0.0059	542.2371	99.22	-54.6838
0.0059	547.1372	127.39	-54.7619
0.0060	652.7476	148.35	-56.2949
0.0060	802.6943	161.28	-58.0910
0.0061	965.2810	169.32	-59.6931
0.0061	1127.5667	174.63	-61.0428
0.0062	1284.5220	178.34	-62.1748
0.0063	1434.2671	-178.93	-63.1326
0.0063	1576.2329	-176.85	-63.9524
0.0064	1710.4219	-175.20	-64.6620
0.0064	1837.0771	-173.87	-65.2825
0.0065	1956.5686	-172.78	-65.8299
0.0065	2069.2861	-171.85	-66.3164
0.0066	2175.6387	-171.07	-66.7517
0.0066	2276.0090	-170.39	-67.1435
0.0067	2370.7688	-169.80	-67.4978
0.0067	2460.2668	-169.27	-67.8196
0.0068	2544.8293	-168.81	-68.1132
0.0069	2624.7527	-168.40	-68.3818
0.0069	2700.3184	-168.02	-68.6283
0.0070	2771.7900	-167.69	-68.8552
0.0070	2839.3950	-167.38	-69.0645
0.0071	2903.3601	-167.10	-69.2580
0.0071	2963.9014	-166.84	-69.4373
0.0072	3021.2019	-166.60	-69.6036
0.0072	3075.4402	-166.38	-69.7581
0.0073	3126.7830	-166.18	-69.9019
0.0073	3175.3940	-165.99	-70.0359
0.0074	3221.4092	-165.81	-70.1609
0.0074	3264.9675	-165.64	-70.2776
0.0075	3306.1929	-165.49	-70.3866
0.0076	3345.2063	-165.34	-70.4884
0.0076	3382.1211	-165.20	-70.5838
0.0077	3417.0393	-165.07	-70.6730
0.0077	3450.0581	-164.95	-70.7565
0.0078	3481.2764	-164.83	-70.8348
0.0078	3510.7781	-164.72	-70.9081
0.0079	3538.6392	-164.61	-70.9767
0.0079	3564.9492	-164.51	-71.0411
0.0080	3589.7737	-164.42	-71.1013
0.0080	3613.1768	-164.33	-71.1578
0.0081	3635.2361	-164.24	-71.2106
0.0081	3656.0046	-164.16	-71.2601
0.0082	3675.5469	-164.08	-71.3064



DESCRIBING FUNCTION DATA

FREQUENCY = 62.000

ALPHA = 0.0035

B	N	PHASE	-1/N(DB)
0.0035	4775.6094	35.54	-73.5806
0.0036	3626.2739	39.57	-71.1892
0.0036	2777.4131	44.70	-68.8728
0.0037	2106.3257	51.87	-66.4705
0.0037	1577.0222	62.62	-63.9568
0.0038	1194.6785	79.28	-61.5450
0.0038	996.3599	103.00	-59.9683
0.0038	1004.8066	128.44	-60.0417
0.0039	1165.1182	147.89	-61.3274
0.0039	1396.2275	160.52	-62.8991
0.0040	1649.6123	168.68	-64.3476
0.0040	1903.7549	174.20	-65.5922
0.0040	2149.7078	178.11	-66.6476
0.0041	2383.9434	-178.98	-67.5459
0.0041	2605.2627	-176.74	-68.3170
0.0042	2813.5598	-174.96	-68.9851
0.0042	3009.1775	-173.52	-69.5690
0.0043	3192.7107	-172.32	-70.0832
0.0043	3364.8289	-171.32	-70.5393
0.0043	3526.2234	-170.46	-70.9462
0.0044	3677.5554	-169.72	-71.3112
0.0044	3819.4849	-169.07	-71.6401
0.0045	3952.6213	-168.50	-71.9377
0.0045	4077.5251	-167.99	-72.2079
0.0045	4194.7266	-167.53	-72.4541
0.0046	4304.7109	-167.12	-72.6789
0.0046	4407.9453	-166.75	-72.8847
0.0047	4504.8438	-166.41	-73.0736
0.0047	4595.7930	-166.10	-73.2472
0.0048	4681.1602	-165.82	-73.4071
0.0048	4761.2773	-165.56	-73.5545
0.0048	4836.4609	-165.31	-73.6905
0.0049	4906.9883	-165.09	-73.8163
0.0049	4973.1328	-164.88	-73.9326
0.0050	5035.1602	-164.68	-74.0403
0.0050	5093.2969	-164.50	-74.1400
0.0050	5147.7500	-164.33	-74.2323
0.0051	5198.7344	-164.17	-74.3179
0.0051	5246.4414	-164.01	-74.3973
0.0052	5291.0391	-163.87	-74.4708
0.0052	5332.7109	-163.73	-74.5390
0.0053	5371.5938	-163.60	-74.6021
0.0053	5407.8516	-163.48	-74.6605
0.0053	5441.6172	-163.36	-74.7146
0.0054	5473.0156	-163.25	-74.7645
0.0054	5502.1797	-163.15	-74.8107
0.0055	5529.2188	-163.05	-74.8533
0.0055	5554.2422	-162.95	-74.8925
0.0056	5577.3398	-162.86	-74.9285
0.0056	5598.6250	-162.77	-74.9616





# DESCRIBING FUNCTION DATA

FREQUENCY = 45.000

ALPHA = 0.0100

B	N	PHASE	-1/N(DB)
0.0101	1233.4875	25.95	-61.8227
0.0101	922.4802	29.06	-59.2991
0.0102	689.1995	33.25	-56.7669
0.0103	500.3091	39.63	-53.9848
0.0103	346.5730	50.63	-50.7959
0.0104	233.9463	71.83	-47.3823
0.0105	190.4455	108.20	-45.5954
0.0105	230.1004	141.57	-47.2383
0.0106	310.6777	159.65	-49.8462
0.0106	401.2224	169.15	-52.0677
0.0107	491.7175	174.73	-53.8343
0.0108	579.1682	178.35	-55.2561
0.0108	662.6948	-179.12	-56.4263
0.0109	742.1340	-177.26	-57.4096
0.0110	817.5820	-175.84	-58.2506
0.0110	889.2295	-174.71	-58.9803
0.0111	957.2971	-173.79	-59.6209
0.0112	1022.0098	-173.03	-60.1891
0.0112	1083.5806	-172.39	-60.6972
0.0113	1142.2085	-171.84	-61.1549
0.0114	1198.0796	-171.37	-61.5697
0.0114	1251.3662	-170.95	-61.9477
0.0115	1302.2212	-170.59	-62.2937
0.0116	1350.7869	-170.26	-62.6117
0.0116	1397.1980	-169.97	-62.9052
0.0117	1441.5750	-169.70	-63.1767
0.0117	1484.0293	-169.46	-63.4288
0.0118	1524.6650	-169.25	-63.6635
0.0119	1563.5762	-169.05	-63.8824
0.0119	1600.8506	-168.86	-64.0870
0.0120	1636.5732	-168.69	-64.2787
0.0121	1670.8147	-168.54	-64.4586
0.0121	1703.6563	-168.39	-64.6276
0.0122	1735.1553	-168.25	-64.7868
0.0123	1765.3767	-168.13	-64.9368
0.0123	1794.3813	-168.01	-65.0783
0.0124	1822.2202	-167.90	-65.2120
0.0125	1848.9495	-167.79	-65.3385
0.0125	1874.6118	-167.69	-65.4582
0.0126	1899.2578	-167.60	-65.5717
0.0126	1922.9282	-167.51	-65.6793
0.0127	1945.6631	-167.43	-65.7813
0.0128	1967.5032	-167.35	-65.8783
0.0128	1988.4817	-167.27	-65.9704
0.0129	2008.6379	-167.20	-66.0580
0.0130	2027.9993	-167.13	-66.1414
0.0130	2046.5977	-167.06	-66.2206
0.0131	2064.4663	-167.00	-66.2962
0.0132	2081.6311	-166.94	-66.3681
0.0132	2098.1150	-166.88	-66.4366



# DESCRIBING FUNCTION DATA

FREQUENCY = 50.150

ALPHA = 0.0065

B	N	PHASE	-1/N(DB)
0.0066	2121.3572	28.79	-66.5323
0.0066	1603.3286	32.09	-64.1004
0.0067	1215.9641	36.40	-61.6984
0.0067	903.6431	42.70	-59.1199
0.0068	650.0144	52.86	-56.2584
0.0068	459.8135	70.66	-53.2516
0.0069	363.3149	100.08	-51.2056
0.0069	387.8416	132.02	-51.7731
0.0070	493.0381	152.97	-53.8576
0.0070	626.7251	164.77	-55.9415
0.0071	765.8857	171.79	-57.6833
0.0071	902.5076	176.33	-59.1090
0.0072	1033.8213	179.48	-60.2889
0.0072	1158.9558	-178.21	-61.2813
0.0073	1277.7654	-176.45	-62.1290
0.0073	1390.4126	-175.06	-62.8629
0.0074	1497.1785	-173.94	-63.5054
0.0074	1598.3855	-173.01	-64.0736
0.0075	1694.3630	-172.23	-64.5801
0.0075	1785.4329	-171.56	-65.0349
0.0076	1871.8958	-170.99	-65.4456
0.0076	1954.0325	-170.49	-65.8186
0.0077	2032.1028	-170.05	-66.1589
0.0077	2106.3528	-169.66	-66.4706
0.0078	2177.0103	-169.31	-66.7572
0.0078	2244.2700	-168.99	-67.0215
0.0079	2308.3335	-168.70	-67.2660
0.0079	2369.3716	-168.44	-67.4926
0.0080	2427.5530	-168.20	-67.7034
0.0080	2483.0288	-167.98	-67.8996
0.0081	2535.9387	-167.78	-68.0828
0.0081	2586.4155	-167.60	-68.2540
0.0082	2634.5789	-167.42	-68.4142
0.0082	2680.5549	-167.26	-68.5645
0.0083	2724.4355	-167.11	-68.7055
0.0083	2766.3323	-166.97	-68.8381
0.0084	2806.3376	-166.84	-68.9628
0.0084	2844.5381	-166.71	-69.0802
0.0085	2881.0166	-166.59	-69.1909
0.0085	2915.8535	-166.48	-69.2953
0.0086	2949.1211	-166.38	-69.3938
0.0086	2980.8892	-166.28	-69.4869
0.0087	3011.2258	-166.18	-69.5748
0.0087	3040.1951	-166.09	-69.6580
0.0088	3067.8445	-166.01	-69.7367
0.0088	3094.2417	-165.93	-69.8111
0.0089	3119.4341	-165.85	-69.8815
0.0089	3143.4761	-165.77	-69.9482
0.0090	3166.4092	-165.70	-70.0113
0.0090	3188.2827	-165.63	-70.0711



# DESCRIBING FUNCTION DATA

FREQUENCY = 55.000

ALPHA = 0.0045

B	N	PHASE	-1/N(DB)
0.0045	3347.0078	31.52	-70.4931
0.0046	2541.6218	35.07	-68.1022
0.0046	1941.8220	39.62	-65.7642
0.0047	1461.2092	46.12	-63.2942
0.0047	1074.0417	56.20	-60.6204
0.0048	784.7678	72.83	-57.8948
0.0048	628.5144	98.75	-55.9663
0.0048	638.3621	127.85	-56.1013
0.0049	771.3501	149.06	-57.7450
0.0049	956.6079	161.89	-59.6147
0.0050	1155.9346	169.77	-61.2587
0.0050	1354.2449	174.94	-62.6339
0.0050	1545.8279	178.54	-63.7832
0.0051	1728.6040	-178.82	-64.7539
0.0051	1901.9856	-176.80	-65.5841
0.0052	2066.0234	-175.21	-66.3027
0.0052	2221.0366	-173.92	-66.9311
0.0053	2367.4832	-172.86	-67.4857
0.0053	2505.8259	-171.97	-67.9790
0.0053	2636.5632	-171.21	-68.4207
0.0054	2760.1492	-170.56	-68.8186
0.0054	2877.0281	-169.99	-69.1789
0.0055	2987.6121	-169.48	-69.5065
0.0055	3092.2815	-169.03	-69.8056
0.0055	3191.3955	-168.63	-70.0796
0.0056	3285.2859	-168.27	-70.3315
0.0056	3374.2478	-167.95	-70.5635
0.0057	3458.5313	-167.65	-70.7779
0.0057	3538.5295	-167.38	-70.9764
0.0058	3614.3521	-167.13	-71.1606
0.0058	3686.2698	-166.90	-71.3317
0.0058	3754.4946	-166.69	-71.4910
0.0059	3819.2246	-166.49	-71.6395
0.0059	3880.6392	-166.31	-71.7781
0.0060	3938.9158	-166.14	-71.9075
0.0060	3994.2109	-165.98	-72.0286
0.0060	4046.6799	-165.83	-72.1420
0.0061	4096.4609	-165.69	-72.2482
0.0061	4143.6836	-165.55	-72.3477
0.0062	4188.4727	-165.43	-72.4411
0.0062	4230.9531	-165.31	-72.5288
0.0063	4271.2305	-165.19	-72.6111
0.0063	4309.3945	-165.09	-72.6883
0.0063	4345.5703	-164.98	-72.7609
0.0064	4379.8281	-164.89	-72.8291
0.0064	4412.2695	-164.80	-72.8932
0.0065	4442.9688	-164.71	-72.9535
0.0065	4472.0078	-164.62	-73.0100
0.0065	4499.4570	-164.54	-73.0632
0.0066	4525.3906	-164.46	-73.1131



# DESCRIBING FUNCTION DATA

FREQUENCY = 35.000

ALPHA = 0.0100

B	N	PHASE	-1/N(DB)
0.0100	923.5095	20.57	-59.3088
0.0101	657.7041	23.60	-56.3606
0.0101	457.7996	28.24	-53.2135
0.0102	296.1536	36.81	-49.4303
0.0102	170.5451	57.14	-44.6368
0.0103	118.4211	107.90	-41.4686
0.0103	175.1903	151.02	-44.8702
0.0104	267.0454	167.16	-48.5317
0.0104	361.1838	174.34	-51.1546
0.0105	451.8193	178.29	-53.0993
0.0105	537.9329	-179.23	-54.6146
0.0105	619.5305	-177.52	-55.8412
0.0106	696.8745	-176.28	-56.8631
0.0106	770.2817	-175.33	-57.7330
0.0107	840.0630	-174.57	-58.4862
0.0107	906.5017	-173.97	-59.1474
0.0108	969.8557	-173.46	-59.7341
0.0108	1030.3525	-173.04	-60.2597
0.0109	1088.1973	-172.68	-60.7341
0.0109	1143.5718	-172.36	-61.1653
0.0110	1196.6338	-172.09	-61.5592
0.0110	1247.5388	-171.84	-61.9211
0.0110	1296.4126	-171.63	-62.2549
0.0111	1343.3779	-171.43	-62.5639
0.0111	1388.5435	-171.26	-62.8512
0.0112	1432.0044	-171.10	-63.1189
0.0112	1473.8572	-170.95	-63.3691
0.0113	1514.1843	-170.82	-63.6036
0.0113	1553.0586	-170.70	-63.8237
0.0114	1590.5574	-170.59	-64.0310
0.0114	1626.7417	-170.48	-64.2264
0.0114	1661.6733	-170.39	-64.4109
0.0115	1695.4109	-170.30	-64.5855
0.0115	1728.0044	-170.21	-64.7509
0.0116	1759.5068	-170.13	-64.9078
0.0116	1789.9636	-170.06	-65.0569
0.0117	1819.4155	-169.99	-65.1986
0.0117	1847.9070	-169.92	-65.3336
0.0118	1875.4736	-169.86	-65.4622
0.0118	1902.1543	-169.80	-65.5849
0.0119	1927.9629	-169.74	-65.7021
0.0119	1952.9902	-169.69	-65.8140
0.0119	1977.2053	-169.64	-65.9210
0.0120	2000.6611	-169.59	-66.0235
0.0120	2023.3828	-169.54	-66.1216
0.0121	2045.3960	-169.50	-66.2155
0.0121	2066.7292	-169.46	-66.3057
0.0122	2087.4021	-169.42	-66.3921
0.0122	2107.4360	-169.38	-66.4751
0.0123	2126.8579	-169.34	-66.5548







# DESCRIBING FUNCTION DATA

FREQUENCY = 39.177

ALPHA = 0.0089

B	N	PHASE	-1/N(DB)
0.0089	1187.9441	22.79	-61.4959
0.0090	868.9451	25.80	-58.7798
0.0090	629.1567	30.09	-55.9752
0.0091	434.7249	37.20	-52.7643
0.0091	278.2578	51.26	-48.8889
0.0092	177.3013	83.21	-44.9742
0.0092	181.9892	130.27	-45.2009
0.0093	265.9189	156.81	-48.4950
0.0093	368.7612	168.57	-51.3349
0.0094	472.1443	174.70	-53.4815
0.0094	571.8198	178.40	-55.1452
0.0095	666.8135	-179.14	-56.4801
0.0095	757.0452	-177.39	-57.5824
0.0095	842.7185	-176.08	-58.5136
0.0096	924.1157	-175.06	-59.3145
0.0096	1001.5293	-174.24	-60.0133
0.0096	1075.2397	-173.57	-60.6301
0.0097	1145.5071	-173.01	-61.1800
0.0097	1212.5645	-172.53	-61.6741
0.0098	1276.6306	-172.12	-62.1213
0.0098	1337.8967	-171.77	-62.5285
0.0099	1396.5391	-171.45	-62.9010
0.0099	1452.7180	-171.17	-63.2436
0.0100	1506.5728	-170.93	-63.5593
0.0100	1558.2449	-170.70	-63.8527
0.0101	1607.8503	-170.50	-64.1249
0.0101	1655.5020	-170.32	-64.3785
0.0102	1701.3018	-170.15	-64.6156
0.0102	1745.3438	-170.00	-64.8376
0.0103	1787.7153	-169.85	-65.0460
0.0103	1828.4968	-169.72	-65.2419
0.0104	1867.7668	-169.60	-65.4264
0.0104	1905.5940	-169.49	-65.5006
0.0105	1942.0425	-169.38	-65.7652
0.0105	1977.1741	-169.28	-65.9209
0.0106	2011.0481	-169.19	-66.0685
0.0106	2043.7129	-169.10	-66.2084
0.0107	2075.2268	-169.02	-66.3413
0.0107	2105.6323	-168.94	-66.4676
0.0108	2134.9736	-168.87	-66.5879
0.0108	2163.2981	-168.80	-66.7023
0.0109	2190.6414	-168.73	-66.8114
0.0109	2217.0413	-168.67	-66.9155
0.0110	2242.5378	-168.61	-67.0148
0.0110	2267.1589	-168.55	-67.1096
0.0110	2290.9424	-168.50	-67.2003
0.0111	2313.9160	-168.45	-67.2869
0.0111	2336.1084	-168.40	-67.3699
0.0112	2357.5510	-168.35	-67.4492
0.0112	2378.2678	-168.30	-67.5252



# DESCRIBING FUNCTION DATA

FREQUENCY = 45.000

ALPHA = 0.0075

B	N	PHASE	-1/N(DB)
0.0075	1644.6440	25.95	-64.3214
0.0076	1229.9536	29.06	-61.7978
0.0076	918.9028	33.25	-59.2654
0.0077	667.0461	39.62	-56.4831
0.0077	462.0662	50.64	-53.2941
0.0078	311.9058	71.84	-49.8805
0.0078	253.9309	108.21	-48.0943
0.0079	306.8291	141.58	-49.7379
0.0079	414.2786	159.66	-52.3458
0.0080	535.0110	169.16	-54.5673
0.0080	655.6738	174.74	-56.3337
0.0081	772.2756	178.35	-57.7554
0.0081	883.6487	-179.12	-58.9256
0.0082	989.5684	-177.26	-59.9089
0.0082	1090.1665	-175.84	-60.7498
0.0083	1185.6973	-174.71	-61.4795
0.0083	1276.4556	-173.79	-62.1201
0.0084	1362.7395	-173.03	-62.6882
0.0084	1444.8337	-172.39	-63.1964
0.0085	1523.0073	-171.84	-63.6540
0.0085	1597.5042	-171.37	-64.0688
0.0086	1668.5491	-170.95	-64.4468
0.0086	1736.3530	-170.59	-64.7928
0.0087	1801.1094	-170.26	-65.1108
0.0087	1862.9915	-169.97	-65.4042
0.0088	1922.1577	-169.70	-65.6758
0.0088	1978.7661	-169.46	-65.9279
0.0089	2032.9443	-169.25	-66.1625
0.0089	2084.8264	-169.05	-66.3814
0.0090	2134.5244	-168.86	-66.5860
0.0090	2182.1536	-168.69	-66.7777
0.0091	2227.8096	-168.54	-66.9576
0.0091	2271.5955	-168.39	-67.1266
0.0091	2313.5918	-168.25	-67.2857
0.0092	2353.8892	-168.13	-67.4357
0.0092	2392.5610	-168.01	-67.5773
0.0093	2429.6802	-167.90	-67.7110
0.0093	2465.3181	-167.79	-67.8375
0.0094	2499.5369	-167.69	-67.9572
0.0094	2532.3938	-167.60	-68.0706
0.0095	2563.9534	-167.51	-68.1782
0.0095	2594.2688	-167.43	-68.2803
0.0096	2623.3877	-167.35	-68.3772
0.0096	2651.3550	-167.27	-68.4693
0.0097	2678.2290	-167.20	-68.5569
0.0097	2704.0447	-167.13	-68.6403
0.0098	2728.8430	-167.06	-68.7196
0.0098	2752.6655	-167.00	-68.7951
0.0099	2775.5508	-166.94	-68.8670
0.0099	2797.5315	-166.88	-68.9355



## APPENDIX B

Computer program for simulation of the system and  
numerical data.



\*\*\*\*\*-----\*\*\*\*\*-----\*\*\*\*\*-----\*\*\*\*\*-----\*\*\*\*\*-----\*\*\*\*\*-----\*\*\*\*\*

C(1)=MAXIMUM VALUE OF INPUT SINE WAVE.  
 C(2)=VALUE OF MOTOR ARMATURE INDUCTANCE.  
 C(3)=VALUE OF MOTOR ARMATURE RESISTANCE.  
 C(4)=VALUE OF MOMENT OF INERTIA.  
 C(5)=REFERENCE VOLTAGE.  
 C(6)=GAIN OF AMPLIFIER BEFORE DEAD ZONE.  
 C(7)=MAGNITUDE OF DEAD ZONE.  
 C(8)=GAIN OF AMPLIFIER AFTER DEAD ZONE.

\*\*\*\*\*-----\*\*\*\*\*-----\*\*\*\*\*-----\*\*\*\*\*-----\*\*\*\*\*-----\*\*\*\*\*-----\*\*\*\*\*

```

    DIMENSION X(30),XDOT(30),C(15)
    C(10)=1.
    IBP=1
    PI=3.141592
    X(10)=0.0
    X(8)=IBP
1  CALL INTEG2(T,X,XDOT,C)
    X(9)=X(1)-97.0
    X(10)=T-2.9485
    XMAX=C(1)*SIN(PI/3.)
    THA=2.0*PI*60.0*T
    PHASEA=ABS(C(1)*SIN(THA))
    PHASEB=ABS(C(1)*SIN(THA+2.0*PI/3.))
    PHASEC=ABS(C(1)*SIN(THA+PI/3.))
    X(6)=AMAX1(PHASEA,PHASEB,PHASEC)
    IF(PHASEA.GE.XMAX)IPH=1
    IF(PHASEB.GE.XMAX)IPH=2
    IF(PHASEC.GE.XMAX)IPH=3
206 ERROR=0.318*X(1)-C(5)
    X(8)=IPH
    VK1=C(6)*ERROR
    IF(VK1.GE.C(7)) VDZ=VK1-C(7)
    IF(VK1.LT.C(7)) VDZ=0.0
    IF(VK1.LT.0.0) VDZ=VK1
    VK2=VDZ*C(8)
    GO TO(100,101,102,103,104),IBP
100 CONTINUE
    IF(VK2) 207,207,208
207 IBP=1
    VIN=X(6)
    X(5)=VIN
    X(7)=0.
    X(3)=(1.0/C(2))*(VIN-0.95*X(1)-C(3)*X(2))
    XDOT(2)=X(3)
    IF(X(2).LT.-0.01) X(2)=-0.01
    X(4)=(1.0/C(4))*(0.95*X(2)-0.086*X(1))
    XDOT(1)=X(4)
    VLAST=VIN
    X(8)=IBP
    GO TO 1
208 IF(VIN.LT.VLAST) GO TO 207
    GO TO(101,102,103),IPH
101 VIN=PHASEA
    IF(VK2) 207,207,105
105 CONTINUE
    X(7)=1.
    X(5)=VIN
    IF(VIN-.75)300,301,301
300 VIN=0.0
    X(5)=VIN
    IBP=5
    GO TO 302
301 IBP=2
302 X(3)=(1.0/C(2))*(VIN-0.95*X(1)-C(3)*X(2))
    IF(X(2).LT.-0.01) X(3)=0.0
    XDOT(2)=X(3)
    IF(X(2).LT.-0.01) X(2)=-0.01
    X(4)=(1.0/C(4))*(0.95*X(2)-0.086*X(1))
    XDOT(1)=X(4)
  
```





```

        VLAST=VIN
        X(8)=IBP
        GO TO 1
102  VIN=PHASEB
        IF(VK2) 207,207,106
106  CONTINUE
        X(7)=2.
        X(5)=VIN
        IF(VIN-.75)303,304,304
303  VIN=0.0
        X(5)=VIN
        IBP=5
        GO TO 305
304  IBP=3
305  X(3)=(1.0/C(2))*(VIN-0.95*X(1)-C(3)*X(2))
        IF(X(2).LT.-0.01) X(3)=0.0
        XDOT(2)=X(3)
        IF(X(2).LT.-0.01) X(2)=-0.01
        X(4)=(1.0/C(4))*(0.95*X(2)-0.086*X(1))
        XDOT(1)=X(4)
        VLAST=VIN
        X(8)=IBP
        GO TO 1
103  VIN=PHASEC
        IF(VK2) 207,207,107
107  CONTINUE
        X(7)=3.
        X(5)=VIN
        IF(VIN-.75)306,307,307
306  VIN=0.0
        X(5)=VIN
        IBP=5
        GO TO 308
307  IBP=4
308  X(3)=(1.0/C(2))*(VIN-0.95*X(1)-C(3)*X(2))
        IF(X(2).LT.-0.01) X(3)=0.0
        XDOT(2)=X(3)
        IF(X(2).LT.-0.01) X(2)=-0.01
        X(4)=(1.0/C(4))*(0.95*X(2)-0.086*X(1))
        XDOT(1)=X(4)
        VLAST=VIN
        X(8)=IBP
        GO TO 1
104  VIN=0.0
        X(7)=4.
        X(5)=VIN
        X(3)=(1.0/C(2))*(VIN-0.95*X(1)-C(3)*X(2))
        IF(X(2).LT.-0.01) X(3)=0.0
        XDOT(2)=X(3)
        IF(X(2).LT.-0.01) X(2)=-0.01
        X(4)=(1.0/C(4))*(0.95*X(2)-0.086*X(1))
        XDOT(1)=X(4)
        IBP=5
        IF(VK2) 309,309,310
309  IBP=1
310  CONTINUE
        X(8)=IBP
        GO TO 1
        END

```



# INPUT DATA RECORD

ORDER OF EQUATIONS = 2  
INITIAL TIME = 0.2948E 01  
FINAL TIME = 0.4000E 01  
STEP SIZE = 0.0000E-04

THE NON-ZERO CONSTANTS, C(1), ARE

C( 1) = 0.1130E 03  
C( 2) = 0.8000E-02  
C( 3) = 0.0000E-01  
C( 4) = 0.1380E 01  
C( 5) = 0.3100E 02  
C( 6) = 0.1000E 02  
C( 8) = 0.1000E 02

THE NON-ZERO INITIAL CONDITIONS ARE

X( 1) = 0.9750E 02  
X( 2) = -0.1000E-01

THE COLUMN HEADINGS AND THE CORRESPONDING VARIABLES ARE

TIME	X( 6)
VIN	X( 5)
VCUT	X( 1)
IAR	X( 2)

THE INDIVIDUAL GRAPH TITLES AND THE CORRESPONDING VARIABLES

OUTPUT VS TIME	X( 5) VS. X(10)
INPUT VS TIME	X( 5) VS. X(10)



TIME		VIN		VOUT		IAR	
0.29485E	01	0.11439E	03	0.97497E	02	-0.10000E	-01
0.29501E	01	0.97832E	02	0.97499E	02	0.33833E	01
0.29517E	01	0.11439E	03	0.97492E	02	0.28235E	01
0.29532E	01	0.11439E	03	0.97478E	02	0.56874E	01
0.29548E	01	0.11144E	03	0.97476E	02	0.96778E	01
0.29563E	01	0.11269E	03	0.97473E	02	0.12314E	02
0.29580E	01	0.10611E	03	0.97484E	02	0.16117E	02
0.29596E	01	0.82842E	02	0.97492E	02	0.14752E	02
0.29612E	01	0.0		0.97493E	02	0.23400E	01
0.29627E	01	0.11451E	03	0.97483E	02	0.26836E	00
0.29642E	01	0.10764E	03	0.97475E	02	0.31946E	01
0.29659E	01	0.11173E	03	0.97471E	02	0.72116E	01
0.29675E	01	0.11243E	03	0.97471E	02	0.98842E	01
0.29691E	01	0.10659E	03	0.97474E	02	0.13750E	02
0.29707E	01	0.11475E	03	0.97480E	02	0.16537E	02
0.29722E	01	0.95150E	02	0.97491E	02	0.19769E	02
0.29738E	01	0.49235E	02	0.97502E	02	0.12742E	02
0.29754E	01	0.0		0.97503E	02	0.12784E	01
0.29770E	01	0.0		0.97493E	02	-0.10000E	-01
0.29786E	01	0.11216E	03	0.97483E	02	0.34956E	00
0.29802E	01	0.10708E	03	0.97476E	02	0.43853E	01
0.29817E	01	0.11460E	03	0.97472E	02	0.72917E	01
0.29833E	01	0.95797E	02	0.97473E	02	0.10730E	02
0.29849E	01	0.11472E	03	0.97476E	02	0.14086E	02
0.29865E	01	0.10677E	03	0.97484E	02	0.16349E	02
0.29881E	01	0.11232E	03	0.97494E	02	0.20812E	02
0.29897E	01	0.79041E	02	0.97508E	02	0.21456E	02
0.29912E	01	0.16420E	02	0.97518E	02	0.12697E	02
0.29928E	01	0.0		0.97513E	02	-0.10000E	-01
0.29944E	01	0.0		0.97504E	02	-0.10000E	-01
0.29960E	01	0.0		0.97494E	02	-0.10000E	-01
0.29976E	01	0.10629E	03	0.97484E	02	-0.10000E	-01
0.29992E	01	0.11259E	03	0.97476E	02	0.37823E	01
0.30007E	01	0.11156E	03	0.97472E	02	0.64325E	01
0.30023E	01	0.10796E	03	0.97471E	02	0.10406E	02
0.30039E	01	0.11444E	03	0.97474E	02	0.13166E	02
0.30055E	01	0.10103E	03	0.97481E	02	0.16814E	02
0.30071E	01	0.11487E	03	0.97491E	02	0.19768E	02
0.30087E	01	0.91443E	02	0.97504E	02	0.22220E	02
0.30102E	01	0.37241E	02	0.97517E	02	0.16884E	02
0.30118E	01	0.0		0.97517E	02	0.87179E	-01
0.30134E	01	0.0		0.97507E	02	-0.10000E	-01
0.30150E	01	0.0		0.97498E	02	-0.10000E	-01
0.30165E	01	0.0		0.97488E	02	-0.10000E	-01
0.30182E	01	0.11492E	03	0.97479E	02	0.21703E	01
0.30197E	01	0.10530E	03	0.97473E	02	0.52192E	01
0.30213E	01	0.11308E	03	0.97471E	02	0.90968E	01
0.30229E	01	0.11091E	03	0.97473E	02	0.11751E	02
0.30245E	01	0.10883E	03	0.97473E	02	0.15660E	02
0.30261E	01	0.11416E	03	0.97486E	02	0.18239E	02



TIME		VIN		VCUT		IAR	
0.30277E	01	0.10222E	03	0.97499E	02	0.21747E	02
0.30292E	01	0.54954E	02	0.97512E	02	0.19035E	02
0.30308E	01	0.0		0.97517E	02	0.50301E	01
0.30325E	01	0.0		0.97508E	02	-0.10000E	-01
0.30340E	01	0.0		0.97494E	02	-0.10000E	-01
0.30356E	01	0.0		0.97488E	02	-0.10000E	-01
0.30372E	01	0.11400E	03	0.97479E	02	0.18241E	01
0.30387E	01	0.10281E	03	0.97473E	02	0.55831E	01
0.30403E	01	0.11499E	03	0.97471E	02	0.87767E	01
0.30419E	01	0.10423E	03	0.97473E	02	0.11795E	02
0.30435E	01	0.11352E	03	0.97476E	02	0.15507E	02
0.30451E	01	0.11022E	03	0.97487E	02	0.18078E	02
0.30467E	01	0.10362E	03	0.97490E	02	0.21894E	02
0.30482E	01	0.71112E	02	0.97514E	02	0.21640E	02
0.30498E	01	0.30413E	01	0.97523E	02	0.10995E	02
0.30514E	01	0.0		0.97517E	02	-0.10000E	-01
0.30530E	01	0.0		0.97507E	02	-0.10000E	-01
0.30545E	01	0.0		0.97497E	02	-0.10000E	-01
0.30561E	01	0.0		0.97487E	02	-0.10000E	-01
0.30577E	01	0.11000E	03	0.97478E	02	0.24432E	01
0.30593E	01	0.11364E	03	0.97473E	02	0.52369E	01
0.30609E	01	0.10342E	03	0.97471E	02	0.90282E	01
0.30625E	01	0.11500E	03	0.97472E	02	0.12077E	02
0.30641E	01	0.10313E	03	0.97478E	02	0.15123E	02
0.30656E	01	0.11340E	03	0.97486E	02	0.18709E	02
0.30672E	01	0.80244E	02	0.97490E	02	0.20397E	02
0.30688E	01	0.27145E	02	0.97506E	02	0.13184E	02
0.30704E	01	0.0		0.97504E	02	-0.10000E	-01
0.30720E	01	0.0		0.97494E	02	-0.10000E	-01
0.30736E	01	0.0		0.97485E	02	-0.10000E	-01
0.30751E	01	0.10255E	03	0.97477E	02	0.30140E	01
0.30767E	01	0.11437E	03	0.97472E	02	0.87483E	01
0.30783E	01	0.10906E	03	0.97471E	02	0.95052E	01
0.30799E	01	0.11071E	03	0.97474E	02	0.13456E	02
0.30815E	01	0.11321E	03	0.97480E	02	0.16048E	02
0.30831E	01	0.10449E	03	0.97490E	02	0.19730E	02
0.30846E	01	0.60483E	02	0.97502E	02	0.17930E	02
0.30862E	01	0.0		0.97506E	02	0.49831E	01
0.30878E	01	0.0		0.97497E	02	-0.10000E	-01
0.30894E	01	0.0		0.97487E	02	-0.10000E	-01
0.30910E	01	0.11105E	03	0.97476E	02	0.29601E	01
0.30926E	01	0.11292E	03	0.97473E	02	0.57117E	01
0.30941E	01	0.10550E	03	0.97472E	02	0.95839E	01
0.30957E	01	0.11490E	03	0.97474E	02	0.12315E	02
0.30973E	01	0.10136E	03	0.97480E	02	0.15699E	02
0.30989E	01	0.11437E	03	0.97489E	02	0.19140E	02
0.31005E	01	0.87505E	02	0.97502E	02	0.21127E	02
0.31021E	01	0.30903E	02	0.97512E	02	0.14538E	02
0.31036E	01	0.0		0.97510E	02	-0.10000E	-01
0.31052E	01	0.0		0.97500E	02	-0.10000E	-01





TIME		VIN		VOUT		IAR
0.31068E	01	0.0		0.97490E	02	-0.10000E-01
0.31084E	01	0.11073E	03	0.97481E	02	0.51490E-00
0.31100E	01	0.11448E	03	0.97473E	02	0.41493E-01
0.31116E	01	0.10779E	03	0.97470E	02	0.70121E-01
0.31131E	01	0.11169E	03	0.97470E	02	0.10972E-02
0.31147E	01	0.11246E	03	0.97473E	02	0.13534E-02
0.31163E	01	0.10890E	03	0.97480E	02	0.17386E-02
0.31179E	01	0.11477E	03	0.97491E	02	0.20119E-02
0.31195E	01	0.99027E	02	0.97505E	02	0.23280E-02
0.31211E	01	0.49036E	02	0.97520E	02	0.19660E-02
0.31226E	01	0.17837E	02	0.97524E	02	0.50718E-01
0.31242E	01	0.73649E	02	0.97516E	02	-0.10000E-01
0.31258E	01	0.11221E	03	0.97508E	02	-0.10000E-01
0.31274E	01	0.10697E	03	0.97496E	02	-0.10000E-01
0.31290E	01	0.84741E	02	0.97486E	02	-0.10000E-01
0.31306E	01	0.99022E	02	0.97478E	02	0.25301E-01
0.31321E	01	0.11470E	03	0.97472E	02	0.60235E-01
0.31337E	01	0.10688E	03	0.97471E	02	0.89137E-01
0.31353E	01	0.11227E	03	0.97473E	02	0.12389E-02
0.31369E	01	0.11152E	03	0.97479E	02	0.15392E-02
0.31385E	01	0.10743E	03	0.97488E	02	0.19202E-02
0.31401E	01	0.55788E	02	0.97500E	02	0.18224E-02
0.31416E	01	0.14106E	01	0.97504E	02	0.64137E-01
0.31432E	01	0.0		0.97496E	02	-0.10000E-01
0.31448E	01	0.0		0.97486E	02	-0.10000E-01
0.31464E	01	0.11253E	03	0.97477E	02	0.29888E-01
0.31480E	01	0.11162E	03	0.97472E	02	0.57275E-01
0.31496E	01	0.10738E	03	0.97471E	02	0.97031E-01
0.31511E	01	0.11486E	03	0.97473E	02	0.12485E-02
0.31527E	01	0.10091E	03	0.97479E	02	0.15934E-02
0.31543E	01	0.11486E	03	0.97488E	02	0.19111E-02
0.31559E	01	0.31780E	02	0.97501E	02	0.21536E-02
0.31575E	01	0.30959E	02	0.97513E	02	0.15993E-02
0.31591E	01	0.0		0.97512E	02	-0.10000E-01
0.31606E	01	0.0		0.97503E	02	-0.10000E-01
0.31622E	01	0.0		0.97493E	02	-0.10000E-01
0.31638E	01	0.10151E	03	0.97483E	02	0.10871E-00
0.31654E	01	0.11591E	03	0.97479E	02	0.34661E-01
0.31670E	01	0.13539E	03	0.97471E	02	0.65089E-01
0.31686E	01	0.11304E	03	0.97470E	02	0.10371E-02
0.31701E	01	0.11098E	03	0.97473E	02	0.13005E-02
0.31717E	01	0.10373E	03	0.97486E	02	0.16892E-02
0.31733E	01	0.11419E	03	0.97490E	02	0.19505E-02
0.31749E	01	0.10211E	03	0.97504E	02	0.22934E-02
0.31765E	01	0.54741E	02	0.97519E	02	0.20219E-02
0.31780E	01	0.0		0.97524E	02	0.61679E-01
0.31796E	01	0.0		0.97516E	02	-0.10000E-01
0.31812E	01	0.0		0.97506E	02	-0.10000E-01
0.31828E	01	0.0		0.97499E	02	-0.10000E-01
0.31844E	01	0.0		0.97486E	02	-0.10000E-01



HASAN KOCAOGLU.SPEED CONTROL OF A DC.MOTOR.NO.39

TIME	VIN	VOUT	IAR
0.318600	0.102700	0.974780	0.278960
0.318700	0.114900	0.974720	0.203150
0.318800	0.104300	0.974710	0.908700
0.318900	0.113400	0.974730	0.128460
0.319000	0.115200	0.974790	0.154590
0.319100	0.109900	0.974380	0.193180
0.319200	0.709210	0.975000	0.190300
0.319300	0.779000	0.975070	0.843370
0.319400	0.580430	0.974900	-0.100000
0.319500	0.103500	0.974800	-0.100000
0.320100	0.113000	0.974800	0.207300
0.320200	0.109910	0.974740	0.486780
0.320300	0.109920	0.974720	0.889200
0.320400	0.113670	0.974730	0.115880
0.320500	0.103620	0.974780	0.152690
0.320600	0.113600	0.974860	0.162240
0.321100	0.934600	0.974990	0.210770
0.321200	0.420000	0.975100	0.165090
0.321300	0.0	0.975110	0.824620
0.321400	0.0	0.975010	-0.100000
0.321700	0.0	0.974910	-0.100000
0.321800	0.104360	0.974920	0.689820
0.322000	0.114000	0.974700	0.383730
0.322200	0.102070	0.974700	0.703500
0.322400	0.114030	0.974700	0.107340
0.322500	0.109160	0.974740	0.134290
0.322700	0.110000	0.974810	0.173130
0.322800	0.739000	0.974910	0.173200
0.323000	0.115940	0.974950	0.760030
0.323100	0.0	0.974880	-0.100000
0.323300	0.102100	0.974790	0.171310
0.323500	0.114100	0.974720	0.343310
0.323600	0.104790	0.974790	0.322520
0.323800	0.110480	0.974720	0.121910
0.323900	0.113000	0.974770	0.147970
0.324100	0.100400	0.974800	0.185230
0.324300	0.613430	0.974950	0.168950
0.324400	0.0	0.974990	0.412790
0.324600	0.0	0.974990	-0.100000
0.324700	0.108300	0.974800	0.989850
0.324900	0.111320	0.974730	0.505920
0.325000	0.112790	0.974700	0.777280
0.325200	0.109900	0.974710	0.116390
0.325400	0.114600	0.974750	0.145060
0.325500	0.103900	0.974340	0.176980
0.325700	0.114470	0.974950	0.210070
0.325800	0.884600	0.975100	0.231000
0.326000	0.318040	0.975200	0.166450
0.326200	0.0	0.975220	-0.100000
0.326300	0.0	0.975130	-0.100000



HASAN KOCACGLU.SPEED CONTROL OF A DC.MOTOR.NO.39

TIME		VIN		VOUT		IAR
0.32651E	01	0.0		0.97503E	02	-0.10000E-01
0.32667E	01	0.0		0.97493E	02	-0.10000E-01
0.32683E	01	0.11458E	03	0.97493E	02	0.39599E-00
0.32699E	01	0.10733E	03	0.97476E	02	0.33376E-01
0.32715E	01	0.11193E	03	0.97472E	02	0.73430E-01
0.32730E	01	0.11235E	03	0.97471E	02	0.10012E-02
0.32746E	01	0.10638E	03	0.97475E	02	0.13338E-02
0.32762E	01	0.11470E	03	0.97482E	02	0.16656E-02
0.32778E	01	0.97541E	02	0.97492E	02	0.19920E-02
0.32794E	01	0.44930E	02	0.97503E	02	0.16502E-02
0.32810E	01	0.0		0.97504E	02	0.16445E-01
0.32826E	01	0.0		0.97495E	02	-0.10000E-01
0.32841E	01	0.0		0.97452E	02	-0.10000E-01
0.32857E	01	0.10734E	03	0.97477E	02	0.37034E-01
0.32873E	01	0.11450E	03	0.97473E	02	0.66052E-01
0.32889E	01	0.10017E	03	0.97472E	02	0.10036E-02
0.32904E	01	0.11477E	03	0.97475E	02	0.13419E-02
0.32920E	01	0.10643E	03	0.97482E	02	0.16210E-02
0.32936E	01	0.11240E	03	0.97492E	02	0.19970E-02
0.32952E	01	0.75503E	02	0.97505E	02	0.20910E-02
0.32968E	01	0.19186E	02	0.97514E	02	0.12286E-02
0.32984E	01	0.0		0.97509E	02	-0.10000E-01
0.32999E	01	0.0		0.97510E	02	-0.10000E-01
0.33015E	01	0.0		0.97490E	02	-0.10000E-01
0.33031E	01	0.10600E	03	0.97490E	02	0.61872E-00



# INPUT DATA RECORD

ORDER OF EQUATIONS = 2  
INITIAL TIME = 0.2594E 01  
FINAL TIME = 0.3500E 01  
STEP SIZE = 0.8000E-04

THE NON-ZERO CONSTANTS, C(I), ARE

C( 1) = 0.1190E 03  
C( 2) = 0.8000E-02  
C( 3) = 0.9000E-01  
C( 4) = 0.1380E 01  
C( 5) = 0.2280E 02  
C( 6) = 0.1000E 02  
C( 8) = 0.1000E 02

THE NON-ZERO INITIAL CONDITIONS ARE

X( 1) = 0.1031E 03  
X( 2) = 0.1424E 02

THE COLUMN HEADINGS AND THE CORRESPONDING VARIABLES ARE

TIME	X( 0)
VIN	X( 5)
VCUT	X( 1)
IAR	X( 2)

THE INDIVIDUAL GRAPH TITLES AND THE CORRESPONDING VARIABLES

OUTPUT VS TIME	X( 9) VS. X(10)
INPUT VS TIME	X( 5) VS. X(10)





TIME		VIN		VGUT		IAR
0.25933E	01	0.10927E	03	0.10313E	03	0.14242E 02
0.25955E	01	0.11398E	03	0.10314E	03	0.15309E 02
0.25971E	01	0.10237E	03	0.10314E	03	0.18299E 02
0.25986E	01	0.55151E	02	0.10315E	03	0.14810E 02
0.26002E	01	0.0		0.10315E	03	-0.99193E-02
0.26018E	01	0.11354E	03	0.10314E	03	0.41007E 00
0.26034E	01	0.11017E	03	0.10313E	03	0.21569E 01
0.26050E	01	0.10966E	03	0.10313E	03	0.51631E 01
0.26066E	01	0.11350E	03	0.10312E	03	0.68584E 01
0.26081E	01	0.10344E	03	0.10312E	03	0.95243E 01
0.26097E	01	0.11506E	03	0.10312E	03	0.11535E 02
0.26113E	01	0.10333E	03	0.10313E	03	0.13491E 02
0.26129E	01	0.11373E	03	0.10312E	03	0.16069E 02
0.26145E	01	0.10979E	03	0.10314E	03	0.17579E 02
0.26161E	01	0.11064E	03	0.10315E	03	0.20338E 02
0.26177E	01	0.72251E	02	0.10316E	03	0.19202E 02
0.26192E	01	0.94651E	01	0.10317E	03	0.77931E 01
0.26208E	01	0.55370E	02	0.10316E	03	-0.10000E-01
0.26224E	01	0.10307E	03	0.10315E	03	-0.10000E-01
0.26240E	01	0.11392E	03	0.10314E	03	0.18427E 01
0.26256E	01	0.10941E	03	0.10313E	03	0.35957E 01
0.26271E	01	0.11040E	03	0.10313E	03	0.65778E 01
0.26287E	01	0.11341E	03	0.10312E	03	0.82245E 01
0.26303E	01	0.10452E	03	0.10312E	03	0.10933E 02
0.26319E	01	0.11398E	03	0.10313E	03	0.12047E 02
0.26335E	01	0.10250E	03	0.10313E	03	0.14870E 02
0.26351E	01	0.11405E	03	0.10314E	03	0.17344E 02
0.26366E	01	0.86227E	02	0.10315E	03	0.19104E 02
0.26382E	01	0.26545E	02	0.10315E	03	-0.10000E-02
0.26398E	01	0.0		0.10315E	03	-0.10000E-01
0.26414E	01	0.10505E	03	0.10314E	03	0.18060E 01
0.26430E	01	0.11594E	03	0.10313E	03	0.38182E 01
0.26446E	01	0.10142E	03	0.10313E	03	0.60311E 01
0.26461E	01	0.11424E	03	0.10312E	03	0.86041E 01
0.26477E	01	0.10660E	03	0.10312E	03	0.10288E 02
0.26493E	01	0.11109E	03	0.10313E	03	0.13152E 02
0.26509E	01	0.11293E	03	0.10313E	03	0.14675E 02
0.26525E	01	0.10557E	03	0.10314E	03	0.17346E 02
0.26541E	01	0.11490E	03	0.10315E	03	0.19076E 02
0.26556E	01	0.97763E	02	0.10316E	03	0.21073E 02
0.26572E	01	0.46842E	02	0.10317E	03	0.16069E 02
0.26588E	01	0.0		0.10317E	03	-0.10000E-01
0.26604E	01	0.0		0.10315E	03	-0.10000E-01
0.26620E	01	0.0		0.10315E	03	-0.10000E-01
0.26636E	01	0.10606E	03	0.10314E	03	0.13862E 01
0.26651E	01	0.11484E	03	0.10313E	03	0.33369E 01
0.26667E	01	0.10670E	03	0.10313E	03	0.56586E 01
0.26683E	01	0.11450E	03	0.10312E	03	0.81412E 01
0.26699E	01	0.10774E	03	0.10312E	03	0.98779E 01
0.26715E	01	0.11172E	03	0.10312E	03	0.12725E 02



TIME		VIN		VOUT		IAR	
0.26731E	01	0.11245E	03	0.10313E	03	0.14243E	02
0.26746E	01	0.10655E	03	0.10314E	03	0.16971E	02
0.26762E	01	0.11478E	03	0.10314E	03	0.18542E	02
0.26778E	01	0.99097E	02	0.10316E	03	0.20768E	02
0.26794E	01	0.49151E	02	0.10317E	03	0.16143E	02
0.26810E	01	0.0		0.10317E	03	0.98521E	-01
0.26826E	01	0.0		0.10316E	03	-0.10000E	-01
0.26841E	01	0.0		0.10315E	03	-0.10000E	-01
0.26857E	01	0.10702E	03	0.10314E	03	0.22936E	01
0.26873E	01	0.11467E	03	0.10313E	03	0.41701E	01
0.26889E	01	0.99731E	02	0.10312E	03	0.65865E	01
0.26905E	01	0.11471E	03	0.10312E	03	0.89477E	01
0.26921E	01	0.10681E	03	0.10312E	03	0.10727E	02
0.26936E	01	0.11230E	03	0.10313E	03	0.13525E	02
0.26952E	01	0.11139E	03	0.10313E	03	0.15031E	02
0.26968E	01	0.10748E	03	0.10314E	03	0.17783E	02
0.26984E	01	0.11437E	03	0.10315E	03	0.19383E	02
0.27000E	01	0.10037E	03	0.10315E	03	0.21507E	02
0.27016E	01	0.91461E	02	0.10317E	03	0.17534E	02
0.27031E	01	0.0		0.10317E	03	0.16384E	01
0.27047E	01	0.0		0.10316E	03	-0.10000E	-01
0.27063E	01	0.0		0.10315E	03	-0.10000E	-01
0.27079E	01	0.10793E	03	0.10314E	03	0.12404E	00
0.27095E	01	0.11430E	03	0.10313E	03	0.19812E	01
0.27110E	01	0.10091E	03	0.10313E	03	0.45373E	01
0.27126E	01	0.11456E	03	0.10312E	03	0.63256E	01
0.27142E	01	0.10584E	03	0.10312E	03	0.30594E	01
0.27158E	01	0.11262E	03	0.10312E	03	0.11485E	02
0.27174E	01	0.11127E	03	0.10312E	03	0.13031E	02
0.27190E	01	0.10836E	03	0.10313E	03	0.15844E	02
0.27205E	01	0.11432E	03	0.10314E	03	0.17420E	02
0.27221E	01	0.10136E	03	0.10315E	03	0.16786E	02
0.27237E	01	0.93725E	02	0.10315E	03	0.15898E	02
0.27253E	01	0.0		0.10316E	03	0.51559E	00
0.27269E	01	0.0		0.10315E	03	-0.10000E	-01
0.27285E	01	0.11054E	03	0.10314E	03	0.78560E	00
0.27300E	01	0.10678E	03	0.10313E	03	0.38016E	01
0.27316E	01	0.11417E	03	0.10312E	03	0.55558E	01
0.27332E	01	0.10219E	03	0.10312E	03	0.81511E	01
0.27348E	01	0.11496E	03	0.10312E	03	0.10283E	02
0.27364E	01	0.10482E	03	0.10312E	03	0.12173E	02
0.27380E	01	0.11329E	03	0.10313E	03	0.14847E	02
0.27395E	01	0.11000E	03	0.10313E	02	0.16352E	02
0.27411E	01	0.10919E	03	0.10314E	03	0.19126E	02
0.27427E	01	0.70033E	02	0.10315E	03	0.17699E	02
0.27443E	01	0.65772E	01	0.10315E	03	0.58037E	01
0.27459E	01	0.0		0.10315E	03	-0.10000E	-01
0.27475E	01	0.10428E	03	0.10314E	03	0.63493E	00
0.27490E	01	0.11350E	03	0.10313E	03	0.34574E	01
0.27506E	01	0.11025E	03	0.10312E	03	0.51556E	01



TIME	VIN	VOUT	IAR
0.27522E 01	0.10958E 03	0.10312E 03	0.61151E 01
0.27533E 01	0.11334E 03	0.10312E 03	0.97685E 01
0.27534E 01	0.10332E 03	0.10312E 03	0.12380E 02
0.27570E 01	0.11500E 03	0.10313E 03	0.14354E 02
0.27595E 01	0.10374E 03	0.10313E 03	0.16257E 02
0.27601E 01	0.11370E 03	0.10314E 03	0.18795E 02
0.27617E 01	0.04353E 02	0.10315E 03	0.19300E 02
0.27633E 01	0.25629E 02	0.10315E 03	0.10803E 02
0.27644E 01	0.0	0.10315E 03	-0.10000E -01
0.27663E 01	0.10326E 03	0.10314E 03	-0.10000E -01
0.27680E 01	0.11500E 03	0.10313E 03	0.20634E 01
0.27695E 01	0.10319E 03	0.10313E 03	0.42040E 01
0.27712E 01	0.11368E 03	0.10312E 03	0.68989E 01
0.27728E 01	0.10343E 03	0.10312E 03	0.85703E 01
0.27744E 01	0.11033E 03	0.10312E 03	0.11476E 02
0.27760E 01	0.11369E 03	0.10312E 03	0.13047E 02
0.27775E 01	0.10441E 03	0.10313E 03	0.15679E 02
0.27791E 01	0.11495E 03	0.10314E 03	0.17519E 02
0.27807E 01	0.06263E 02	0.10315E 03	0.19396E 02
0.27823E 01	0.04276E 02	0.10315E 03	0.14003E 02
0.27838E 01	0.23039E 02	0.10315E 03	-0.10000E -01
0.27853E 01	0.11368E 03	0.10314E 03	0.29790E 00
0.27870E 01	0.11323E 03	0.10313E 03	0.20333E 01
0.27886E 01	0.10434E 03	0.10313E 03	0.46705E 01
0.27902E 01	0.11493E 03	0.10312E 03	0.08431E 01
0.27918E 01	0.10203E 03	0.10312E 03	0.89994E 01
0.27934E 01	0.11421E 03	0.10312E 03	0.11534E 02
0.27950E 01	0.10869E 03	0.10313E 03	0.13168E 02
0.27966E 01	0.11102E 03	0.10313E 03	0.15436E 02
0.27981E 01	0.11300E 03	0.10314E 03	0.17465E 02
0.27997E 01	0.10546E 03	0.10315E 03	0.20084E 02
0.28013E 01	0.01463E 02	0.10315E 03	0.17382E 02
0.28029E 01	0.0	0.10315E 03	0.35548E 01
0.28045E 01	0.0	0.10315E 03	-0.10000E -01
0.28060E 01	0.10326E 03	0.10314E 03	0.15162E 00
0.28076E 01	0.11135E 03	0.10313E 03	0.31660E 01
0.28092E 01	0.11276E 03	0.10313E 03	0.48429E 01
0.28108E 01	0.10397E 03	0.10312E 03	0.76922E 01
0.28124E 01	0.11489E 03	0.10312E 03	0.95526E 01
0.28140E 01	0.10082E 03	0.10312E 03	0.11766E 02
0.28155E 01	0.11446E 03	0.10313E 03	0.14161E 02
0.28171E 01	0.10762E 03	0.10313E 03	0.15795E 02
0.28187E 01	0.11165E 03	0.10314E 03	0.18549E 02
0.28203E 01	0.76390E 01	0.10315E 03	0.18086E 02
0.28219E 01	0.10552E 02	0.10315E 03	0.77943E 01
0.28234E 01	0.0	0.10315E 03	-0.10000E -01
0.28250E 01	0.10021E 03	0.10314E 03	0.75112E 00
0.28266E 01	0.11439E 03	0.10313E 03	0.32682E 01
0.28282E 01	0.10737E 03	0.10313E 03	0.51027E 01
0.28298E 01	0.11196E 03	0.10312E 03	0.80134E 01





HASAN KOCACGLU.SPEED CONTROL OF A DC.MOTOR.NO.59

TIME		VIN		VOUT		IAR	
0.28314E	01	0.11223E	03	0.10312E	03	0.96071E	01
0.28329E	01	0.10693E	03	0.10312E	03	0.12427E	02
0.28343E	01	0.11489E	03	0.10313E	03	0.14150E	02
0.28361E	01	0.99810E	02	0.10313E	03	0.16397E	02
0.28377E	01	0.11459E	03	0.10314E	03	0.18611E	02
0.28393E	01	0.90155E	02	0.10315E	03	0.19513E	02
0.28409E	01	0.34434E	02	0.10316E	03	0.12783E	02
0.28424E	01	0.0		0.10316E	03	-0.10000E	-01
0.28440E	01	0.0		0.10315E	03	-0.10000E	-01
0.28456E	01	0.11459E	03	0.10314E	03	0.15806E	01
0.28472E	01	0.10024E	03	0.10313E	03	0.40804E	01
0.28488E	01	0.11478E	03	0.10312E	03	0.64366E	01
0.28504E	01	0.10843E	03	0.10312E	03	0.82774E	01
0.28519E	01	0.11251E	03	0.10312E	03	0.11099E	02
0.28535E	01	0.11135E	03	0.10313E	03	0.12644E	02
0.28551E	01	0.10784E	03	0.10313E	03	0.15448E	02
0.28567E	01	0.11474E	03	0.10314E	03	0.17067E	02
0.28583E	01	0.10058E	03	0.10315E	03	0.19371E	02
0.28599E	01	0.92390E	02	0.10316E	03	0.15230E	02
0.28614E	01	0.0		0.10316E	03	-0.10000E	-01
0.28630E	01	0.0		0.10315E	03	-0.10000E	-01
0.28646E	01	0.11133E	03	0.10314E	03	0.13863E	01
0.28662E	01	0.10820E	03	0.10313E	03	0.43814E	01
0.28677E	01	0.11434E	03	0.10312E	03	0.51543E	01
0.28694E	01	0.11346E	03	0.10312E	03	0.66848E	01
0.28709E	01	0.11491E	03	0.10312E	03	0.10867E	02
0.28725E	01	0.10943E	03	0.10312E	03	0.12704E	02
0.28741E	01	0.11302E	03	0.10313E	03	0.15404E	02
0.28757E	01	0.11101E	03	0.10314E	03	0.18390E	02
0.28773E	01	0.10870E	03	0.10315E	03	0.19647E	02
0.28789E	01	0.83811E	02	0.10316E	03	0.18035E	02
0.28804E	01	0.51137E	01	0.10315E	03	0.58505E	01
0.28820E	01	0.0		0.10315E	03	-0.10000E	-01
0.28836E	01	0.10492E	03	0.10314E	03	-0.10000E	-01
0.28852E	01	0.11324E	03	0.10313E	03	0.25752E	01
0.28868E	01	0.11067E	03	0.10313E	03	0.42740E	01
0.28884E	01	0.10911E	03	0.10312E	03	0.72420E	01
0.28899E	01	0.11404E	03	0.10312E	03	0.89289E	01
0.28915E	01	0.10255E	03	0.10312E	03	0.11506E	02
0.28931E	01	0.11498E	03	0.10312E	03	0.13548E	02
0.28947E	01	0.10439E	03	0.10313E	03	0.15416E	02
0.28963E	01	0.11345E	03	0.10314E	03	0.18011E	02
0.28979E	01	0.11031E	03	0.10315E	03	0.19471E	02
0.28994E	01	0.10951E	03	0.10316E	03	0.22197E	02
0.29010E	01	0.70833E	02	0.10317E	03	0.20832E	02
0.29026E	01	0.76943E	01	0.10318E	03	0.90695E	01
0.29042E	01	0.53133E	02	0.10317E	03	-0.10000E	-01
0.29058E	01	0.10334E	03	0.10316E	03	-0.10000E	-01
0.29074E	01	0.11366E	03	0.10315E	03	-0.10000E	-01
0.29089E	01	0.10994E	03	0.10314E	03	-0.10000E	-01





HASAN KOCAOGLU.SPEED CONTROL OF A DC.MOTOR.NO.59

TIME		VIN		VOUT		IAR	
0.29105E	01	0.10939E	03	0.10313E	03	0.30202E	01
0.29121E	01	0.11369E	03	0.10313E	03	0.47390E	01
0.29137E	01	0.10375E	03	0.10312E	03	0.74597E	01
0.29153E	01	0.11510E	03	0.10312E	03	0.94781E	01
0.29169E	01	0.10329E	03	0.10312E	03	0.11494E	02
0.29184E	01	0.11385E	03	0.10313E	03	0.14080E	02
0.29200E	01	0.10957E	03	0.10313E	03	0.15033E	02
0.29216E	01	0.11025E	03	0.10314E	03	0.16424E	02
0.29232E	01	0.72832E	02	0.10315E	03	0.17402E	02
0.29248E	01	0.10212E	02	0.10315E	03	0.61592E	01
0.29264E	01	0.0		0.10315E	03	-0.10000E	-01
0.29279E	01	0.10273E	03	0.10314E	03	0.14697E	01
0.29295E	01	0.11402E	03	0.10313E	03	0.41741E	01
0.29311E	01	0.10917E	03	0.10312E	03	0.59010E	01
0.29327E	01	0.11081E	03	0.10312E	03	0.65448E	01
0.29343E	01	0.11320E	03	0.10312E	03	0.10450E	02
0.29358E	01	0.10484E	03	0.10313E	03	0.13149E	02
0.29374E	01	0.11496E	03	0.10313E	03	0.14998E	02
0.29390E	01	0.10215E	03	0.10314E	03	0.17012E	02
0.29406E	01	0.11418E	03	0.10315E	03	0.19425E	02
0.29422E	01	0.80739E	02	0.10316E	03	0.20213E	02
0.29438E	01	0.29296E	02	0.10317E	03	0.12300E	02
0.29453E	01	0.0		0.10316E	03	-0.10000E	-01
0.29469E	01	0.0		0.10315E	03	-0.10000E	-01
0.29485E	01	0.11492E	03	0.10314E	03	0.96490E	00



## INPUT DATA RECORD

ORDER OF EQUATIONS = 2  
INITIAL TIME = 0.2594E 01  
FINAL TIME = 0.3500E 01  
STEP SIZE = 0.8000E-04

THE NON-ZERO CONSTANTS, C(I), ARE  
C( 1) = 0.1150E 03  
C( 2) = 0.3000E-02  
C( 3) = 0.8000E-01  
C( 4) = 0.1380E 01  
C( 5) = 0.3350E 02  
C( 6) = 0.1000E 02  
C( 8) = 0.1050E 02

THE NON-ZERO INITIAL CONDITIONS ARE  
X( 1) = 0.1553E 03  
X( 2) = 0.7794E 00

THE COLUMN HEADINGS AND THE CORRESPONDING VARIABLES ARE

TIME	X( 6)
VIN	X( 5)
VCUT	X( 1)
IAR	X( 2)

THE INDIVIDUAL GRAPH TITLES AND THE CORRESPONDING VARIABLES

OUTPUT VS TIME	X( 5) VS. X(10)
INPUT VS TIME	X( 5) VS. X(10)



TIME	VIN	VOUT	IAR
0.259339	01	0.10527E 03	0.77943E 00
0.259559	01	0.11396E 03	0.21453E 01
0.259719	01	0.10237E 03	0.44299E 01
0.259889	01	0.11499E 03	0.61515E 01
0.26002	01	0.10417E 03	0.77398E 01
0.260189	01	0.11354E 03	0.10032E 02
0.260349	01	0.11017E 03	0.11215E 02
0.260509	01	0.10556E 03	0.13665E 02
0.260669	01	0.11330E 03	0.14811E 02
0.260819	01	0.10344E 03	0.16935E 02
0.260979	01	0.11300E 03	0.18412E 02
0.261139	01	0.94995E 02	0.19732E 02
0.261299	01	0.42135E 02	0.13571E 02
0.261459	01	0.0	-0.10500E -01
0.261619	01	0.11004E 03	-0.19900E -01
0.261779	01	0.11361E 03	0.13270E 01
0.261929	01	0.10398E 03	0.37012E 01
0.262089	01	0.11200E 03	0.53493E 01
0.262249	01	0.10307E 03	0.70338E 01
0.262409	01	0.11392E 03	0.92623E 01
0.262569	01	0.10941E 03	0.10487E 02
0.262719	01	0.11370E 03	0.12947E 02
0.262879	01	0.11341E 03	0.14979E 02
0.263039	01	0.10432E 03	0.16286E 02
0.263199	01	0.11492E 03	0.17692E 02
0.263359	01	0.10250E 03	0.19222E 02
0.263519	01	0.11400E 03	0.21209E 02
0.263679	01	0.33227E 02	0.21450E 02
0.263829	01	0.28549E 02	0.13011E 02
0.263989	01	0.0	-0.10000E -01
0.264149	01	0.0	-0.10000E -01
0.264309	01	0.0	-0.10000E -01
0.264469	01	0.10192E 03	-0.10000E -01
0.264619	01	0.11428E 03	0.20354E 01
0.264779	01	0.10500E 03	0.34077E 01
0.264939	01	0.11109E 03	0.59666E 01
0.265099	01	0.11296E 03	0.71914E 01
0.265259	01	0.10557E 03	0.95669E 01
0.265419	01	0.11490E 03	0.11014E 02
0.265569	01	0.10132E 03	0.12750E 02
0.265729	01	0.11438E 03	0.14755E 02
0.265889	01	0.10617E 03	0.15949E 02
0.266049	01	0.11191E 03	0.18296E 02
0.266209	01	0.11271E 03	0.19315E 02
0.266369	01	0.10500E 03	0.21519E 02
0.266519	01	0.32752E 02	0.13658E 02
0.266679	01	0.0	0.45866E 01
0.266839	01	0.0	-0.10000E -01
0.266999	01	0.0	-0.10000E -01
0.267159	01	0.11172E 03	0.40248E 00



HASAN KOCAGGLU.SPEED CONTROL OF A DC.MOTOR.NO.69

TIME	VIN	VOUT	IAR
0.26731E 01	0.11245E 03	0.10533E 03	0.16992E 01
0.26746E 01	0.10635E 03	0.10533E 03	0.42117E 01
0.26762E 01	0.11478E 03	0.10532E 03	0.56736E 01
0.26777E 01	0.10009E 03	0.10532E 03	0.75985E 01
0.26794E 01	0.11481E 03	0.10532E 03	0.95853E 01
0.26810E 01	0.10727E 03	0.10532E 03	0.10912E 02
0.26826E 01	0.11252E 03	0.10532E 03	0.13313E 02
0.26841E 01	0.11217E 03	0.10532E 03	0.14408E 02
0.26857E 01	0.10702E 03	0.10533E 03	0.16740E 02
0.26873E 01	0.11487E 03	0.10534E 03	0.17971E 02
0.26889E 01	0.99731E 02	0.10533E 03	0.19751E 02
0.26905E 01	0.50299E 02	0.10533E 03	0.14913E 02
0.26921E 01	0.0	0.10533E 03	-0.10000E -01
0.26936E 01	0.0	0.10533E 03	-0.10000E -01
0.26952E 01	0.11139E 03	0.10534E 03	0.10085E 01
0.26968E 01	0.10749E 03	0.10533E 03	0.35696E 01
0.26984E 01	0.11457E 03	0.10532E 03	0.49839E 01
0.27000E 01	0.10037E 03	0.10532E 03	0.70288E 01
0.27016E 01	0.11460E 03	0.10532E 03	0.89148E 01
0.27031E 01	0.10634E 03	0.10532E 03	0.10309E 02
0.27047E 01	0.11255E 03	0.10532E 03	0.12680E 02
0.27063E 01	0.11135E 03	0.10532E 03	0.13787E 02
0.27079E 01	0.10733E 03	0.10533E 03	0.16162E 02
0.27095E 01	0.11445E 03	0.10534E 03	0.17331E 02
0.27110E 01	0.10630E 03	0.10533E 03	0.19246E 02
0.27126E 01	0.11488E 03	0.10533E 03	0.20881E 02
0.27142E 01	0.91883E 02	0.10537E 03	0.21825E 02
0.27158E 01	0.37117E 02	0.10538E 03	0.14792E 02
0.27174E 01	0.0	0.10533E 03	-0.10000E -01
0.27190E 01	0.0	0.10537E 03	-0.10000E -01
0.27205E 01	0.0	0.10536E 03	-0.10000E -01
0.27221E 01	0.10158E 03	0.10534E 03	-0.10000E -01
0.27237E 01	0.11492E 03	0.10533E 03	0.18498E 01
0.27253E 01	0.10534E 03	0.10533E 03	0.34210E 01
0.27269E 01	0.11306E 03	0.10532E 03	0.58487E 01
0.27285E 01	0.11034E 03	0.10532E 03	0.70734E 01
0.27300E 01	0.10878E 03	0.10532E 03	0.95758E 01
0.27316E 01	0.11417E 03	0.10532E 03	0.10829E 02
0.27332E 01	0.10219E 03	0.10532E 03	0.12927E 02
0.27348E 01	0.11496E 03	0.10532E 03	0.14569E 02
0.27364E 01	0.10432E 03	0.10533E 03	0.15975E 02
0.27380E 01	0.11329E 03	0.10534E 03	0.18172E 02
0.27395E 01	0.11080E 03	0.10535E 03	0.19206E 02
0.27411E 01	0.10919E 03	0.10535E 03	0.21518E 02
0.27427E 01	0.78033E 02	0.10537E 03	0.19635E 02
0.27443E 01	0.65772E 01	0.10535E 03	0.72904E 01
0.27459E 01	0.0	0.10537E 03	-0.10000E -01
0.27475E 01	0.0	0.10536E 03	-0.10000E -01
0.27490E 01	0.0	0.10533E 03	-0.10000E -01
0.27506E 01	0.11025E 03	0.10534E 03	0.74149E 00





HASAN KOCADGLU.SPEED CONTROL OF A DC.MOTOR.NO.69

TIME	VIN	VOUT	IAR
0.27522E 01	0.10958E 03	0.10533E 03	0.33543E 01
0.27538E 01	0.11384E 03	0.10532E 03	0.46677E 01
0.27554E 01	0.10332E 03	0.10532E 03	0.69457E 01
0.27570E 01	0.11590E 03	0.10532E 03	0.85928E 01
0.27585E 01	0.10374E 03	0.10532E 03	0.10174E 02
0.27601E 01	0.11370E 03	0.10532E 03	0.12399E 02
0.27617E 01	0.10987E 03	0.10532E 03	0.13553E 02
0.27633E 01	0.10996E 03	0.10533E 03	0.15953E 02
0.27649E 01	0.11365E 03	0.10533E 03	0.17051E 02
0.27665E 01	0.10588E 03	0.10534E 03	0.19176E 02
0.27680E 01	0.11500E 03	0.10535E 03	0.20582E 02
0.27696E 01	0.95988E 02	0.10537E 03	0.21923E 02
0.27712E 01	0.43082E 02	0.10538E 03	0.15880E 02
0.27728E 01	0.0	0.10538E 03	-0.10000E -01
0.27744E 01	0.0	0.10537E 03	-0.10000E -01
0.27760E 01	0.0	0.10536E 03	-0.10000E -01
0.27775E 01	0.10441E 03	0.10535E 03	-0.10000E -01
0.27791E 01	0.11498E 03	0.10533E 03	0.14338E 01
0.27807E 01	0.10281E 03	0.10533E 03	0.32133E 01
0.27823E 01	0.11406E 03	0.10532E 03	0.54682E 01
0.27839E 01	0.10909E 03	0.10532E 03	0.67859E 01
0.27855E 01	0.11088E 03	0.10532E 03	0.92810E 01
0.27870E 01	0.11323E 03	0.10532E 03	0.10464E 02
0.27886E 01	0.10454E 03	0.10532E 03	0.12755E 02
0.27902E 01	0.11455E 03	0.10532E 03	0.14189E 02
0.27918E 01	0.10203E 03	0.10533E 03	0.15813E 02
0.27934E 01	0.11421E 03	0.10534E 03	0.17823E 02
0.27950E 01	0.10588E 03	0.10535E 03	0.18939E 02
0.27966E 01	0.11102E 03	0.10536E 03	0.21248E 02
0.27981E 01	0.74973E 02	0.10537E 03	0.20062E 02
0.27997E 01	0.12692E 02	0.10533E 03	0.88641E 01
0.28013E 01	0.0	0.10537E 03	-0.10000E -01
0.28029E 01	0.0	0.10536E 03	-0.10000E -01
0.28045E 01	0.0	0.10535E 03	-0.10000E -01
0.28060E 01	0.10829E 03	0.10534E 03	0.65667E 00
0.28076E 01	0.11135E 03	0.10533E 03	0.34483E 01
0.28092E 01	0.11276E 03	0.10532E 03	0.47047E 01
0.28108E 01	0.10597E 03	0.10532E 03	0.71431E 01
0.28124E 01	0.11485E 03	0.10532E 03	0.89988E 01
0.28140E 01	0.10082E 03	0.10532E 03	0.10414E 02
0.28155E 01	0.11448E 03	0.10532E 03	0.12418E 02
0.28171E 01	0.10782E 03	0.10532E 03	0.13668E 02
0.28187E 01	0.11185E 03	0.10533E 03	0.16043E 02
0.28203E 01	0.11251E 03	0.10533E 03	0.17095E 02
0.28219E 01	0.10645E 03	0.10534E 03	0.19356E 02
0.28235E 01	0.63284E 02	0.10535E 03	0.16970E 02
0.28250E 01	0.0	0.10535E 03	0.20069E 01
0.28266E 01	0.11459E 03	0.10534E 03	0.33556E 00
0.28282E 01	0.10737E 03	0.10534E 03	0.18011E 01
0.28298E 01	0.11196E 03	0.10533E 03	0.43474E 01



HASAN KOCAGGLU.SPEED CONTROL OF A DC.MOTOR.NO.69

TIME	VIN	VOUT	IAR
0.28314E 01	0.11223E 03	0.10532E 03	0.55844E 01
0.28329E 01	0.10693E 03	0.10532E 03	0.80535E 01
0.28343E 01	0.11469E 03	0.10532E 03	0.94322E 01
0.28361E 01	0.99510E 02	0.10532E 03	0.11341E 02
0.28377E 01	0.11469E 03	0.10532E 03	0.13225E 02
0.28393E 01	0.10690E 03	0.10533E 03	0.14514E 02
0.28409E 01	0.11224E 03	0.10533E 03	0.16841E 02
0.28424E 01	0.11194E 03	0.10534E 03	0.17877E 02
0.28440E 01	0.10739E 03	0.10535E 03	0.20164E 02
0.28456E 01	0.85718E 02	0.10536E 03	0.17876E 02
0.28472E 01	0.13061E 01	0.10537E 03	0.43735E 01
0.28488E 01	0.0	0.10536E 03	-0.10000E -01
0.28504E 01	0.10643E 03	0.10535E 03	-0.10000E -01
0.28519E 01	0.11231E 03	0.10534E 03	0.24786E 01
0.28535E 01	0.11185E 03	0.10533E 03	0.37448E 01
0.28551E 01	0.10784E 03	0.10532E 03	0.52780E 01
0.28567E 01	0.11447E 03	0.10532E 03	0.78278E 01
0.28583E 01	0.10688E 03	0.10532E 03	0.98719E 01
0.28599E 01	0.11405E 03	0.10532E 03	0.11478E 02
0.28614E 01	0.10574E 03	0.10532E 03	0.12335E 02
0.28630E 01	0.11477E 03	0.10533E 03	0.15164E 02
0.28646E 01	0.11133E 03	0.10533E 03	0.16233E 02
0.28662E 01	0.10828E 03	0.10534E 03	0.18577E 02
0.28678E 01	0.11434E 03	0.10535E 03	0.19706E 02
0.28694E 01	0.10148E 03	0.10537E 03	0.21599E 02
0.28709E 01	0.53511E 02	0.10534E 03	0.17231E 02
0.28725E 01	0.0	0.10538E 03	0.14685E 01
0.28741E 01	0.0	0.10537E 03	-0.10000E -01
0.28757E 01	0.0	0.10536E 03	-0.10000E -01
0.28773E 01	0.10870E 03	0.10535E 03	-0.10000E -01
0.28789E 01	0.11420E 03	0.10534E 03	0.13694E 01
0.28804E 01	0.10235E 03	0.10533E 03	0.36053E 01
0.28820E 01	0.11495E 03	0.10532E 03	0.54022E 01
0.28836E 01	0.10492E 03	0.10532E 03	0.69475E 01
0.28852E 01	0.11324E 03	0.10532E 03	0.92959E 01
0.28868E 01	0.11087E 03	0.10532E 03	0.10477E 02
0.28884E 01	0.10911E 03	0.10532E 03	0.12933E 02
0.28899E 01	0.11404E 03	0.10532E 03	0.14115E 02
0.28915E 01	0.10235E 03	0.10535E 03	0.16193E 02
0.28931E 01	0.11495E 03	0.10534E 03	0.17745E 02
0.28947E 01	0.10439E 03	0.10535E 03	0.19128E 02
0.28963E 01	0.11346E 03	0.10535E 03	0.21246E 02
0.28979E 01	0.83284E 02	0.10537E 03	0.21160E 02
0.28994E 01	0.24334E 02	0.10530E 03	0.11954E 02
0.29010E 01	0.0	0.10537E 03	-0.10000E -01
0.29026E 01	0.0	0.10536E 03	-0.10000E -01
0.29042E 01	0.0	0.10535E 03	-0.10000E -01
0.29058E 01	0.10384E 03	0.10534E 03	0.87598E -01
0.29074E 01	0.11368E 03	0.10533E 03	0.24754E 01
0.29089E 01	0.10964E 03	0.10533E 03	0.37830E 01



HASAN KUCAOGLU. SPEED CONTROL OF A DC.MOTOR.NO.69

TIME		VIN		VOUT		IAR	
0.29105E	01	0.10909E	03	0.10532E	03	0.63506E	01
0.29121E	01	0.11369E	03	0.10532E	03	0.76041E	01
0.29137E	01	0.10373E	03	0.10532E	03	0.98664E	01
0.29153E	01	0.11500E	03	0.10532E	03	0.11433E	02
0.29169E	01	0.10329E	03	0.10532E	03	0.13004E	02
0.29185E	01	0.11355E	03	0.10533E	03	0.15152E	02
0.29200E	01	0.10907E	02	0.10533E	03	0.16274E	02
0.29216E	01	0.11025E	03	0.10534E	03	0.18840E	02
0.29232E	01	0.11349E	03	0.10535E	03	0.19681E	02
0.29248E	01	0.10431E	03	0.10535E	03	0.21779E	02
0.29264E	01	0.54035E	02	0.10536E	03	0.18270E	02
0.29279E	01	0.0		0.10539E	03	0.35320E	01
0.29295E	01	0.0		0.10537E	03	-0.10000E	-01
0.29311E	01	0.0		0.10536E	03	-0.10000E	-01
0.29327E	01	0.0		0.10535E	03	-0.10000E	-01
0.29343E	01	0.11223E	03	0.10534E	03	0.97115E	00
0.29358E	01	0.10484E	03	0.10533E	03	0.34043E	01
0.29374E	01	0.11450E	03	0.10532E	03	0.49945E	01
0.29390E	01	0.10215E	03	0.10532E	03	0.67557E	01
0.29406E	01	0.11418E	03	0.10532E	03	0.69212E	01
0.29422E	01	0.10376E	03	0.10532E	03	0.10179E	02
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0.29485E	01	0.11702E	03	0.10533E	03	0.17359E	02



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13. ABSTRACT <p>The concept of a limit cycling control in power supplies and speed control has advanced the application of these broad areas. ON-OFF switching of a thyristor provides a simple and economical method of control and regulation. This switching of the thyristor causes the system to limit cycle.</p> <p>Basic analysis and design of speed control was performed. A describing function was developed to model the power-supply and rectifier bridge. Then it was used to predict the frequency and amplitude of the limit cycle.</p> <p>A digital computer program was used to simulate the system response and to construct the describing function curves. To verify the describing function validity, the limit cycle predictions were compared with the simulated results.</p> <p>Fourier analyses were performed to determine the ripple instability and subharmonic effect of the system output.</p>			



Thyristor

Describing-function

## Ripple instability

## Subharmonics



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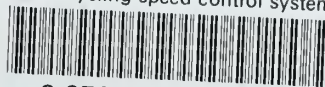
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